ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Aykut SÖNMEZ

MODELING OF DOUBLY-FED INDUCTION GENERATOR BASED POWER SUPPLY SYSTEM FOR AIRCRAFT APPLICATIONS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

ADANA, 2020

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We certify that the thesis titled above was reviewed and approved for the award of the degree of the Master of Science by the board of jury on 21/05/2020

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ABSTRACT

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With developing aircraft technologies, there has been a significant increase in electrical equipment in aircraft. The increase in the electrical equipment used in aircraft caused an increase in energy demand. Therefore, the implementation of stronger and more reliable electricity generation, transmission, and storage methods has become an imperative concern for aircraft. In this thesis study, it has been studied to adapt the doubly-feed induction generator which produces constant output at variable speeds by eliminating the mechanical constant speed drive in the turbine generator, which is the main electric source of the aircraft. Firstly, the structure of DFIG has been researched and comprehended and its working principle has been assimilated. Afterwards, DFIG which can operate in isolated regions, designed for the production of electricity aircraft. Flyback converter, inverter and a asynchronous generator are used for modeling of the system.

Keywords: Aircraft electric generation systems, Wind tribune types, Generator types, Doubly-Fed Induction Generator, Variable speed constant frequency and voltage, Flyback converter, Standalone operation, DFIG design for aircraft

ÖZ

YÜKSEK LİSANS TEZİ

ÇİFT-BESLEMELİ İNDÜKSİYON JENERATÖRÜ BAZLI GÜÇ KAYNAĞI MODELLENMESİNİN UÇAKLARDAKİ UYGULMASI

Aykut SÖNMEZ

ÇUKUROVA ÜNİVERSİTESİ
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Günümüzde gelişen teknolojiye ve ihtiyaç duyulan donanıma paralel olarak uçaklarda ciddi bir elektriksel donanım artışı olduğu görülmektedir. Gelişmelere bağlı olarak artan elektriksel elemanların artmasıyla beraber uçaklardaki güç talebi de artış göstermiştir. Bu da beraberinde daha güçlü ve güvenilir bir elektrik üretim iletim ve depolama yöntemlerinin uygulanması bir zorunluluk haline gelmiştir. Gelişen ve eklenen elektriksel ekipmanlara bağlı olarak uçakların mevcut elektrik sistemleri de zaman zaman yetersizlik gösterir hale gelmiştir. Güç üretim kapasitesi bakımından bir yetersizlik yaşanmamasına karşın daha güvenilir ve sade güç sistemlerinin arayışı devam etmektedir. Bu tez çalışmasında da uçakların ana elektrik kaynağı olan türbin jeneratöründe bulunan mekanik sabit hız sürücüsünü elimine ederek değişken devirlerde sabit çıkış üreten çift beslemeli indüksiyon jeneratörünün uçaklara uyarlanması üzerine çalışılmıştır. İlk olarak DFIG yapısı araştırılmış ve kavranmış ve çalışma prensibi özümsenmiştir. Sistemin modellenmesinde flyback konverter, inverter ve asenkron jenerator kullanılmıştır.

Anahtar Kelimeler: Uçak elektrik üretim sistemleri, Rüzgar Jeneratör tipleri, Çift Beslemeli İndüksiyon Jeneratörü, Değişken hız sabit frekans ve gerilim, Flayback çevirici, İzole durum operasyonu, Uçaklar için DFIG modellenmesi.

GENİŞLETİLMİŞ ÖZET

Günümüzde sivil havacılık ve seyahat, yük ve kargo taşımacılığı, savunma ve hobi amaçlı kullanımlar için uçaklar vazgeçilmez bir öneme ve değere sahiptir. Yaşanılan kazalarda can ve mal kayıpların fazla olmasından dolayı, zaman zaman tehlikeli bir ulaşım seçeneği olarak değerlendirilebilen hava yolculuğu ve taşımacılığı, aslına bakılırsa kara ve deniz taşımacılığına göre son derece daha güvenli ve önemli derecede daha hızlı bir yolculuk biçimidir.

Son asırda uçaklar üzerinde gerçekleştirilen yeniliklere ve gelişmelere baktığımızda çığır açar nitelikte bir teknolojik ilerlemenin olduğu görülmektedir. Dünyamızda ilk üretilen uçakların ilk çalıştırılma şekline baktığımızda manuel bir pompa yardımı ile yanma odasına gönderilen yakıtın el ile çekilerek çalıştırılan bir başlatıcı ile gerçekleştiği görülür. Burada ki prensip el ile düşük devirde çalıştırılan uçak motoru ilk hareketi aldıktan sonra motor şaftına bağlı bir indüksiyon bobini sayesinde basit bir ateşleme sistemi ile çalışmasına dayanır. Diğer yandan tüm kontrol ve kumanda işleri mekanik, pünomatik tetikleyiciler ile yapılırken, basit bir radyo haberleşme ve sinyalizasyon sistemi dahi uçaklarda bulunmayabiliyordu.

İlk uçaklarda motorlar için gelişmiş bir elektrikli tetikleyici motoru ve basit bir radyo haberleşme sistemi bile bulunmuyorken, günümüzdeki uçaklar çok daha farklı ve büyük boyutlara ulaşan bir elektromekanik, radyo, kontrol, sinyalizasyon ve eğlence sistemleri gibi birçok elektriksel donanıma sahiptir. Haliyle gelişen ve artan bu bileşenler uçaklar için güçlü ve güvenilir bir elektrik kaynağı ihtiyacını hayati biçimde artırmıştır. Ve günümüz uçaklarının güvenilirliği ve konforu için, aerodinamik ve tüm mekanik tasarımları kadar elektriksel sisteminin de en az o kadar öneme sahip olduğu söylenebilir.

Günümüzde uçakların elektrik enerjisini karşılamak için mevcut bulunan beş farklı yöntem bulunmaktadır. Bunlara yakından bakıldığında ilk olarak harici güç kaynağı göze çarpmaktadır. Bu sistem uçak yerde ve tamamen dinlenme durumundayken şehir şebekesinden aldığı alternatif akım elektrik enerjisini uçak için uygun olan 400 Hz 115 V değerlerine getirerek harici bir güç soketi ile uçağı besleyen sistemidir. Uçağın tüm sistemleri kapalıyken bakım ve kontrol yapılması için tercih edilir. Buna ek olarak tüm bataryaların dolu tutulmasında da rol oynar.

İkinci sisteme bakıldığında ise uçağın kuyruk kısmına yerleştirilmiş olan yardımcı güç ünitesi görülür. Gücünü dizel bir motordan alan bu sistem, uçağın harici gücü kesildikten sonra çalışmaya hazırlandığı evrede uçağın tüm güç ihtiyacını karşılamaya yardım eder. Bataryaların tam şarj olmasını sağlar. Ve uçak jet türbin motorları çalışma evresindeyken gerekli olan ilk başlangıç enerjisini sağlamak için yüksek basınçlı hava üreterek tetikleyici başlatıcı sisteminin aktif olmasını sağlar. En önemli görevlerinden biri budur çünkü uçakların devasa türbinlerini çalıştırmak için gereken enerji elektrikli bir motorla sağlanacak olsa idi yüksek güçte ve fiziksel olaraktan ağır sistemlerin kurulması gerekecekti. Uçuş boyunca normal şartlar altında türbinler çalışmaya başladıktan sonra otomatik olarak kapanır ve devreden çıkar. Buna ek olarak uçuş anında meydana gelebilecek olan türbin ya da ana jeneratör arızası durumunda üretimi eksik kalan enerjinin üretilmesi için devreye girerek elektrik üretir. İsmi yardımcı güç ünitesi olarak geçen bu sistemin aslına bakıldığında uçağın birçok fonksiyonunu yerine getiren, eksikliğinde bir takım yetersizliklerin baş gösterebileceği, çok önemli bir bileşen olduğu görülür.

Doğru akım ile çalışan bileşenlerin görevini yerine getirebilmesi için ve olası bir alternatif akım enerjisi üretememe durumunda depolanmış elektrik enerjisi teminini sağlayabilmek için uçaklarda güçlü bir doğru akım şebekesi ve batarya guruplarının olması ile mümkün olur. Uçakların DC güç şebekesi, enerjiyi her an kullanıma hazır şekilde depolayan güçlü batarya sistemleri, bataryaların ful şarj olmasını ve doğru akım şebekesini besleyen alternatif akım şebekesinden aldığı enerjiyi doğru akıma çeviren transformatör doğrultucu ünitesi olmak üzere iki ana başlık olarak görülür. Bunların yanında farklı gerilimlerde doğru akım için kullanılan çeviriciler ve bütün alternatif akım kaynakları tükendiğinde eldeki mevcut depolanmış doğru akım enerjisini bataryalardan alarak alternatif akıma çeviren invertör sistemi bulunur. Doğru akım şebekeleri genel olarak birbirine paralel olarak bağlı olan iki farklı ana şebekeden meydana gelir. Bu iki paralel doğru akım hattının her biri gücünü yine birbirine paralel olarak bağlı olan iki alternatif akım hattından alır. Herhangi bir hatta arıza olduğu durumda diğer hattan paralel olarak beslenebilme özelliğine sahiptir.

Uçakta bulunan en küçük kapasiteli güç sistemine bakıldığında acil durumlarda otomatik olarak veya pilotun isteği ile devreye giren acil durum jeneratörleri görülür. Genel olarak uçağın burun kısmında bir adet veya her bir kantta birer adet gizli olarak bulunan bu mekanizma genel olarak kullanılma oranı en düşük olan sistemdir. Çünkü kullanılabilecek durumun ortaya çıkabilmesi için uçağın tüm alternatif akım enerjisi üreten sistemlerinin işlevsiz hale gelmesi gerekir ki bu da yardımcı güç ünitesin bozulması veya yakıtının bitmesi ya da türbin ana jeneratörlerinin bozulması ve yine yakıt problemi yaşanması anlamına gelir ve bu çok düşük bir ihtimaldir. Enerjisini uçağın süzülüş enerjisinden alan bu mekanizma sinyalizasyon ve haberleşme için yetecek kadar asgari enerjiyi üretmenin yanında arkasında bulunan küçük bir yağ pompası sayesinde bazı mekanik sistemlerin manuel olarak kontrolünü sağlamak için basınçlı hidrolik yağ pompasına sahiptir.

Son ve esas olarak bakıldığında görülen sistem is uçağın türbinleri çalıştıktan sonra tüm enerjisini sağlayan türbin ana jeneratörleridir. Temel yapı olarak senkron jeneratör tipinde olan bu makineler küçük bir tolerans payı ile sabit hızda çalışarak uçağın ihtiyaç duyduğu elektrik enerjisini karşılar. İhtiyaç duyduğu mekanik enerjiyi sabit hız sürücüsü olarak bilinen bir mekanik ara yüz aracılığı ile uçak türbinlerinden alır. Sabit hız sürücüsünün temel görevi uçağın türbininden aldığı değişken devirli mekanik girişi, içerisinde bulunan değişken yağ akış debisine göre ayarlayarak istenilen hıza getiren sistemdir. Sabit hız sürücüsü veya uçak türbin motorlarından birinin arıza yapması durumunda türbin ana jeneratörlerinin çalışması mümkün değildir.

Son yıllarda uçaklarda artan elektronik aksamlar beraberinde getirdiği fazla güç talebi ile uçakların üretmesi gereken elektrik enerjisini bariz bir atış göstermiştir. Bu artana enerji talebini karşılamak için daha güçlü bir elektrik üretim sistemi gerekirken diğer yandan daha sade ve güvenilir özellikleri de beraberinde taşıması gereken sistemlerin tasarımına gidilmiştir. Yıllardır uçaklarda kullanılagelen senkron jeneratör ve sabit hız sürücü sisteminin bir arada kullanılması talep edilen toplam enerjiyi sunabilmekte yeterli olmakla birlikte bir takım sorunları da beraberinde getirmektedir. Bu sorunların en başında fiziksel ağırlık ve hacim ile birlikte sık arıza ve bakım ihtiyaçları gelmektedir. Yapısı gereği değişken yağ akış akısı ve hızı ile değişken olarak aldığı mekanik hızı istenilen hıza sabitleyen sabit hız sürücüsü çok zaman yağ kaçakları ve akış kontrol valfleri sorunları ve arızaları yaşamaktadır. Buna ek olarak düşük verimli yapısı, çok gürültülü ve titreşimli çalışması da bir başka dezavantaj olarak ortaya çıkar.

Günümüzde rüzgar türbinlerinde yaygın ve etkin olarak kullanılmakta olan çift beslemeli indüksiyon jeneratörleri yapısı olarak rotorun bir çevirici aracılığı ile stator terminalinden beslenerek değişken hızlarda sabit gerilim ve frekansta alternatif akım enerjisi üretmeye dayanır. Mevcut şebekeden aldığı enerjiyi kontrol gurubunun ürettiği modülasyona göre forma sokarak rotora sürer ve aldığı geri besleme sinyalleri neticesinde bu modülasyona şekil vererek stator terminal değerleri kontrol altında tutulur ve sabit parametrelerle sürdürülmesi sağlanır.

Çift beslemeli indüksiyon jeneratörleri içi iki farklı kullanım topolojisi bulunmaktadır. Bunlardan ilki mevcut bir şebeke ile bağlantının bulunduğu sistemlerdir ve rotorun ihtiyaç duyduğu manyetik enerjiyi elde etmek için hali hazırda bulunan şebeke kullanılır. Bir diğer sistem ise izole bölgelerde bulunan ve herhangi bir şebekeye bağlı olmadan tek başına çalışan izole bölge çift beslemeli indüksiyon jeneratörleri sistemleridir.

Temel topolojisi değişken hızlarda asenkron motor aracılığı ile sabit frekans ve gerilimde elektrik enerjisi üretmek olan izole bölge çift beslemeli indüksiyon jeneratörleri yapı olarak değişken devir ile çalışan uçak türbinlerine uygun olarak düşünülebilir. Bu şekilde elimine edilecek olan bir çift sabit hız sürücüsü, her ana jeneratör için birer tane, uçağın tasarımında ciddi bir kütle azalmasına ve mekanik sadeliğe olanak verir. Diğer yandan bu sistemin elimine edilmesiyle beraber servis ihtiyacı ve sık arıza verme durumları da ortadan kalkmış olur.

Bu hedeflenen değişikliğin esas avantajı ise asenkron jeneratör ile elde dilecek olan sabit frekans ve gerilimde alternatif akım enerjisinin daha etkin verimli bir şekilde elde edilebiliyor olmasıdır. Kontrol aşamasında rotor ve stator akım ve gerilim değerlerinin d ve q bileşenleri alınarak PID kontrolcü aracılığı ve şebeke ile rotor arası açı farkının hesaplanması ile kontrol sinyalleri belirlenir. Bu sinyaller rotor taraflı çevirici aracılığı ile üç faz gerçek rotor akım ve gerilim değerlerine modüle edilerek çevrilir. Bu şekilde sürekli bir geri besleme tekniği uygulanarak stator parametreleri kontrol altında tutulmuş olur. Buradaki bir diğer avantaj ise jet türbin hızının uçuş şartları ve ihtiyacına göre değişmesinden ve sisteme eklenen ya da çıkan bir yük gurubunun enerji arzından bağımsız olmak üzere hızlı bir şekilde sitemin istenilen parametrelere dönerek sistem kararlılığını sağlamasıdır.

Bu tez çalışmasında günümüz modern uçakları için büyük öneme sahip olan ana türbin jeneratörlerinin alışılageldik sabit devir sabit frekans ve gerilim (SDSFV) sisteminin uygulanması yerine, rüzgar türbinlerinde kullanılan Çift Beslemeli İndüksiyon Jeneratörlerinin (ÇBİJ) uygulanması üzerine çalışılmıştır. Uçuş şartlarına bağlı olarak değişken hızlarda dönen jet türbin motorundan alınan mekanik enerjinin basit bir orana sahip dişli kutusundan geçerek ÇBİJ hareket ettirmesi, giriş devri ve yük değişiminden bağımsız olarak sabit frekans ve gerilimde alternatif akım üretmesi üzerine çalışılmıştır. Tasarlanan sistemin analizi MATLAB-Simulink ile analiz edilmiş ve sonuçlar alınmıştır. ÇBİJ sisteminin değişik hangi alanlarda kullanıldığının, farklı kontrol yöntemlerinin nasıl sonuç verdiği üzerine çalışılmış olup, temel hedef olan bu sistemin uçaklara uygulanması üzerinde durulmuştur.

DETAILED ABSTRACT

Today, aircrafts are very important for civil aviation and travel, cargo and cargo transportation, defense, and the other use. Due to the high life and property loss in accidents, air travel, and transportation, which can be considered as a dangerous transportation option sometimes. But it is an extremely safer and significantly faster method of transportation than land and sea transportation.

While the first aircraft did not even have an advanced electric trigger motor and a simple radio communication system for engines, today's aircraft have much electrical equipment such as electromechanical, radio, control, signaling, and entertainment systems that reach much different and larger dimensions. These developing and increasing components have vitally increased the need for a strong and reliable source of electricity for aircraft.

Today, there are five different methods available to meet the electrical energy of aircraft. With care a closer look at them, first of all, the external power source stands out. This system is the system that feeds the aircraft with an external power socket by bringing the alternating current electrical energy it receives from the city network to the 400 Hz 115 V values suitable for the aircraft while the plane is on the ground and completely at rest. It is preferred for maintenance and control when all aircraft systems are closed. Also, it plays a role in keeping all batteries charged.

Looking at the second system, the auxiliary power unit located in the tail of the plane is seen. This system, which takes its power from a diesel engine, helps to meet all the power needs of the aircraft in the phase where the aircraft is prepared to work after the external power is cut off. It ensures that the batteries are fully charged. And the aircraft jet turbine engines produce high-pressure air to provide the initial starting energy required while in operation, enabling the trigger starter system to be active. This is one of their most important tasks because if the energy needed to run the huge turbines of the planes was provided by an electric motor, high-power, and

physically heavier systems would have to be installed. During the flight, the turbines automatically shut down and turn off after the turbines start to operate under normal conditions. Also, in the event of a turbine or main generator failure that may occur at the time of flight, it activates to produce the energy that is missing its production and generates electricity. When the system is named as the auxiliary power unit, it can be seen that it is a very important component that performs many functions of the aircraft, where some deficiencies may arise in its deficiency.

It is possible with a strong direct current network and battery groups in the aircraft so that the components working with direct current can fulfill their duties and provide stored electrical energy in case of not being able to produce a possible alternating current energy. The DC power grid of airplanes is seen as two main titles: powerful battery systems that store energy ready for use at any time, transformer rectifier unit that converts the batteries from a full charge, and alternating current network feeding the direct current network to direct current. In addition to these, there are converters used for direct current at different voltages and an inverter system that converts the current stored direct current energy from the batteries to alternative current when all alternative current sources are exhausted. Direct current networks generally consist of two different main networks connected in parallel. Each of these two parallel direct current lines gets its power from two alternating current lines that are connected in parallel to each other. It has the feature of feeding parallel to the other line in case of failure in any line.

When looking at the smallest capacity power system on the plane, emergency generators that are activated automatically in emergencies or at the request of the pilot are seen. Generally, this mechanism, which is hidden in the nose part of the aircraft or one in each, is the system with the lowest rate of use in general. Because for the situation that can be used to occur, all alternating current energy generating systems of the aircraft must become dysfunctional, which means that the auxiliary power unit is out of order or out of fuel, or turbine main generators are broken, and this is a very low probability. This mechanism, which takes its energy from the gliding energy of the aircraft, has a pressurized hydraulic oil pump to provide manual control of some mechanical systems thanks to a small oil pump located behind it, as well as producing minimum energy sufficient for signaling and communication.

The last and mainly viewed system is the turbine's main generators that provide all its energy after the turbines of the aircraft are operating. These machines, which are in synchronous generator type as the basic structure, work at a constant speed with small tolerance, and meet the electrical energy required by the aircraft. It takes the mechanical energy it needs from aircraft turbines through a mechanical interface known as a constant speed drive. The main task of the constant speed driver is the system that adjusts the variable speed mechanical inlet received from the turbine of the aircraft to the desired speed by adjusting it according to the variable oil flow rate in it. In the event of a fixed speed drive or one of the aircraft turbine engine malfunctions, the turbine main generators cannot be operated.

In recent years, with the increasing demand for power, the increased electronic components in the aircraft have shown an obvious shot to the electrical energy that the aircraft must produce. To meet this increasing energy demand, a stronger electricity generation system is required, on the other hand, the systems that need to carry more simple and reliable features have been designed. The combination of the synchronous generator and constant speed drive system, which has been used in aircraft for years, is sufficient to offer the total energy demand, but it also brings some problems. Frequent breakdown and maintenance needs, along with physical weight and volume, are at the top of these problems. The constant speed drive, which fixes the mechanical speed it receives as a variable with the variable oil flow flux and speed due to its structure, suffers from oil leaks and flow control valves problems and failures. Besides, its low-efficiency structure, very noisy and vibrating operation is another disadvantage.

Doubly-fed induction generators, which are widely used in wind turbines today, are based on generating alternating current energy with constant voltage and frequency at variable speeds by feeding the rotor from the stator terminal through a converter. According to the modulation produced by the control group, the energy it receives from the existing network takes form into the rotor and as a result of the feedback signals it receives, it is shaped by this modulation and the stator terminal values are kept under control and maintained with constant parameters.

There are two different usage topologies for doubly-fed induction generators. The first of these is the systems where there is a connection with an existing network and the existing network is used to obtain the magnetic energy required by the rotor. Another system is the isolated zone doubly-fed induction generators systems located in isolated regions and working alone without being connected to any network.

Isolated zone doubly-fed induction generators whose basic topology is to produce electrical energy at constant frequency and voltage through the asynchronous motor at variable speeds can be considered under aircraft turbines operating at variable speed as a structure. A pair of constant speed drives to be eliminated in this way allows one for each main generator, a significant mass reduction in the design of the aircraft and mechanical simplicity. On the other hand, by eliminating this system, the need for service and frequent failures are eliminated.

In this thesis, instead of constant speed synchronous machines used in aircraft, asynchronous machine design giving constant output at variable speeds has been studied. The DFIG model with a stable stator output is designed regardless of the turbine speed, which indicates the flight conditions with Matlab Simulink. At the same time, DFIG has been studied and investigated in detail in other areas of its use. how different control methods work, and the main target is to apply this system to aircraft. What are the DFIG control mechanisms and what is the most appropriate control mechanism for this model, is studied.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	: Alternating Current
APU	: Auxiliary Power Unit
ATRU	: Auto-Transformer Rectifier Unit
CSCF	: Constant Speed Constant Frequency
CSD	: Constant Speed Driver
DC	: Direct Current
DFIG	: Doubly-Fed Induction Generator
DPC	: Direct Power Control
DT/D	: Duty Cycle
DVC	: Direct Voltage Control
F/RWSG	: Field/Rotor Winding Synchronous Generator
GR	: Glide Ratio
HVDC	: High Voltage Direct Current
IDG	: Integrated Driven Generator
MG	: Main Generator
PI	: Proportional Integration
PID	: Proportional Integration Differentiation
PMSG	: Permanent Magnet Synchronous Generator
PWM	: Pulse Width Modulation
RAM	: Ram Air Tribune
RPM	: Revolution Per Unit
RSC	: Rotor Side Converter
SSC	: Stator Side Converter
TRU	: Transformer Rectifier Unit
VA (P)	: Active Power
VAR (Q)	: Reactive Power
VC	: Vector Control

VSCF	: Variable Speed Constant Frequency
VSVF	: Variable Speed Variable Frequency
n_d	: Driven Speed
n_s	: Synchronous Speed
∅	: Magnetic Flux
d-q	: Park Transformation of D-Q Frame
N	: Number of Revolution Per Minute
p	: Number of Pole Pairs
S	: Slip Percent
f	: Electrical Frequency (Hz)
$\alpha - \beta$	: Clarke Transformation of $\alpha - \beta$ Frame
ε	: Induced Voltage
μ	: Magnetic Permeability

1. INTRODUCTION

1.1. Background, Problem Determination, and Research Motivation

Over the years, due to the increase in electrical components and equipment that have evolved in aircraft, a stronger and more reliable power generation, transmission, and distribution system has become a necessity. In the early days, while designing and developing more mechanical designs on airplanes, the electrical systems of the aircraft became a vital field of study due to the increasing needs and added equipment (Jones R. et al., 1999).

A strong and reliable electrical system is of paramount importance when air travel as airplanes is considered. This is because, in case of a failure, the intervention and repair of the aircraft until landing on the runway can result in a difficult or even impossible situation. For this reason, the innovations that have emerged as a result of the developments in parallel with the needs over the years have become insufficient from time to time and have become an open and compulsory field for development.

As time passed, due to the increasing technological innovations and the much equipment needed to be added to the aircraft, the required electrical energy demanded on the aircraft increased significantly (Avery C. R., et al, 2007). For example, some of this added equipment can be given as an example by providing mechanical, hydraulic, and pneumatic actuator systems partially or completely with electrical activators, or entertainment systems offered to passengers during the flight and in-air conditioning systems (Avery C. R., et al, 2007). As a result of these developments and needs, it can said that the generation efficiency and reliability of electric power in aircraft is an extremely important and critical task. (Feehally T., and Judith M., 2015).

The development of a simple and compact power generation system with high reliability and efficiency, with the power to feed the entire aircraft system, with low maintenance and service requirements, is a matter of study due to the reasons mentioned above. Currently, the most widely used main generator (MG) system is powered by a constant speed drive (CSD) mechanical turbine from the aircraft turbine, generating a constant voltage at a constant shaft speed (generally 6000 RPM) and an alternating current at a frequency, which can be produced per main generator The amount of electrical energy can be up to 500 kVA (Moir I. and AllaN S., 2011). In principle, the operation of the constant speed drive is based on the variable mechanical oil flow or variable mechanical rotation speed it receives from the input to the output at the desired fixed speed amount (Hucker D. J., 1966).

One of the biggest disadvantages when generating electricity with the induction generator used integrated with CSD is low efficiency and this efficiency is measured as a maximum of 72% (). Both the mechanical and hydraulic system, the noisy and inefficient operating system and the physical weight, frequent maintenance requirements, combined with the constant speed drive integrated drive generator (IDG) system more reliable, compact, efficiently and physically lighter less it has led to the search for new power generation systems that require maintenance.

One of the options that can be considered at this stage is that one of the systems that can be suitable for the turbine engine that can rotate at variable speeds depending on the flight conditions and the instantaneous flight situation, which is similar to the variable speed characteristics of the wind turbines, can be said to be Doubly-Fed Induction Generators (DFIG). DFIG can be defined as obtaining an alternating current with constant frequency and voltage output at variable mechanical speeds in a range of 1: 1.67 times to 1: 0.72 times of the synchronous speed, within the range of -40% + 40% of the synchronous speed, within a certain range of the general characteristic (M. Tazil et al., 2010; L. Chengwu et al. 2002).

The main object of this study is to eliminate the constant CSD in the IDG used in the main turbine generators used in aircraftinstead of obtaining electrical energy from the double-feed induction generator connected to the turbine shaft with a simple gear ratio. The main objective was to keep the frequency and voltage values of the control system constant, regardless of the input speed that may show sudden changes and any load changes to and from the system. While this control scheme is in progress, the instantaneous current to be given to the rotor is determined by measuring the voltage and current values measured at the stator terminals by generating the appropriate PWM wave through the PI controller. These methods are discussed in direct voltage control (DVC), a direct power control (DPC) and vector control (VC) frameworks.

1.2. Subject and Aim of This Thesis

This thesis aims to model the doubly-fed induction generator used in wind turbines to give output at preferred 400 Hz frequency and 115 V voltage which is used in aircrafts different from 220 V and 50 Hz values in city network and to obtain simulation result. Besides, the comparison of direct DVC and VC and DPC methods used in the control of double-fed induction generators is also emphasized. Model; asynchronous induction generator as a DFIG, PI-based controller, PWM module for feeding the rotor side converter, start-up capacitor to provide energy for initial voltage formation at built-up, a boost converter which is used for RSC feeding on 28 V DC power of aircraft with the amplified form of higher DC value.

After the introduction of the problem statement, research motivation, and contribution of the research, the structure of this thesis is as follows.

The second part includes the general definition of the electrical system used in modern airplanes, what components it consists of, what voltage and frequency values are used and why these values are preferred, all electrical generation systems and storage methods will be examined and a wide literature review will be conducted.

The third chapter focuses on the general structure of DFIG used in wind turbines, their operating principles, the methods used in their controls, and most importantly, the examination and compilation of the studies showing how the isolated zone DFIG applications are similar to the system to be used in aircraft as well as general circuit design basic equations and equations and control diagrams are examined.

In the fourth chapter, the reactions of the system for different situations are examined and the similarity and agreement between the expected and the obtained simulation results are examined and compared. The result is that the system maintains its stability and returns to the desired reference values with the fastest response when the mechanical speed changes or when any load group is included in the system. The stability of the system is examined and evaluated for such changeable situations.

In the fifth chapter, a large-scale evaluation of the results was made and the results of the study were explained. Innovative works topics which can be done in the future is discussed.

1.3. Outputs and Contributions of the Thesis

The main results of this thesis, its contributions, and the results which is obtained can be listed as follows:

i) Through a comprehensive literature review, how the electrical system used in aircraft since the beginning, the methods of generating and storing electricity, and in which case a source is used,

ii) How the DFIG operation and control system works and how this mechanism is done and how the stand-alone DFIG system is controlled, how the initial start-up is performed and how it is controlled while the operation is in progress, what differences are involved in maintaining this process in the isolated region, which control algorithms are used and what challenges are to be overcome,

iii) What changes and advantages are the application of the DFIG system to airplanes and how they contribute to flight comfort and safety, Comprehensive knowledge about the subject is researched by examining, researching, and comparing in detail.

2. RESEARCH ON THE ELECTRICAL SYSTEM OF AIRCRAFT

2.1. Aircraft Electrical Systems

Before the airplanes became an important part of life and started to be produced in series, the main issues were focused on aerodynamic structure, flight dynamics, fuselage statics and materials used (E. D. Ganev, 2007). In parallel with the developing technology, the electricity needs of the aircraft have increased and the development of a strong and reliable electricity generation and distribution system has become obligatory (X. Roboam, 2011).

Induction generators are the places where almost all of the electrical energy production in aircraft is obtained. The main structure of the system is largely similar to the generation of electrical energy from the induction generators used on earth. An initial driving mechanical energy supplied from the generator shaft moves to the desired synchronous circuit and moves the rotor and alternating electric flux is generated from the stator to generate alternating electrical energy (Cao W. et al. 2012) (Arumugam P. et al., 2014).

$$f = \frac{N.p}{120} \tag{2.1}$$

This equation shows the relationship between frequency (f), number of poles (individual not in pairs) (p), and mechanical speed (N) for synchronous machines (A. A. Tatevosyan et al., 2017).

The parameters of the electric energy used in aircraft are 400Hz / 115v, unlike 50Hz / 220V (Weimer J., 2013, 2013; Moir I., AllaN S., 2011). The advantage why high frequency voltage is used in aircraft, one is to be able to carry more intense energy in the same time period and the other is using thinner cable. (Boglietti A. et al., 2009). The second and more important reason is to minimize the effect of the skin effect factor, which is characterized by its electro-magnetic characteristic and alternating current (AC) transmission lines. To enable the use of a thinner cross-section and thus to create a lighter and lower-cost transmission and distribution installation.

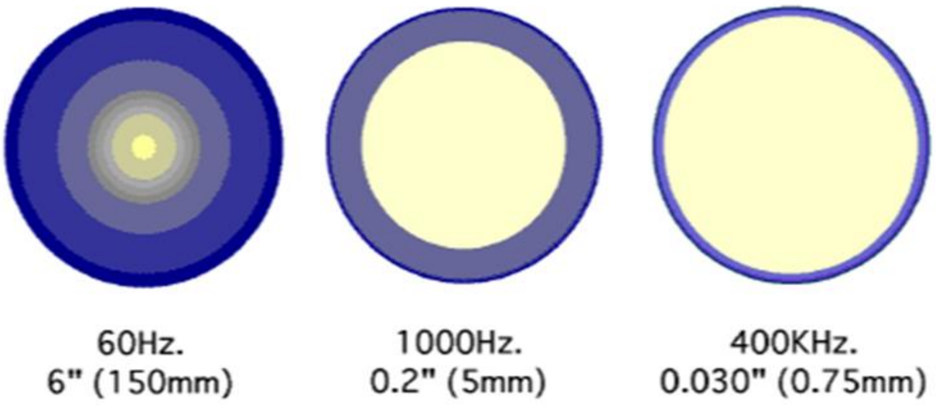

Figure 2.1. Skin Effect: Current penetration depth in stell (current shown in blue) (Alan Chris D'souza, 2015).

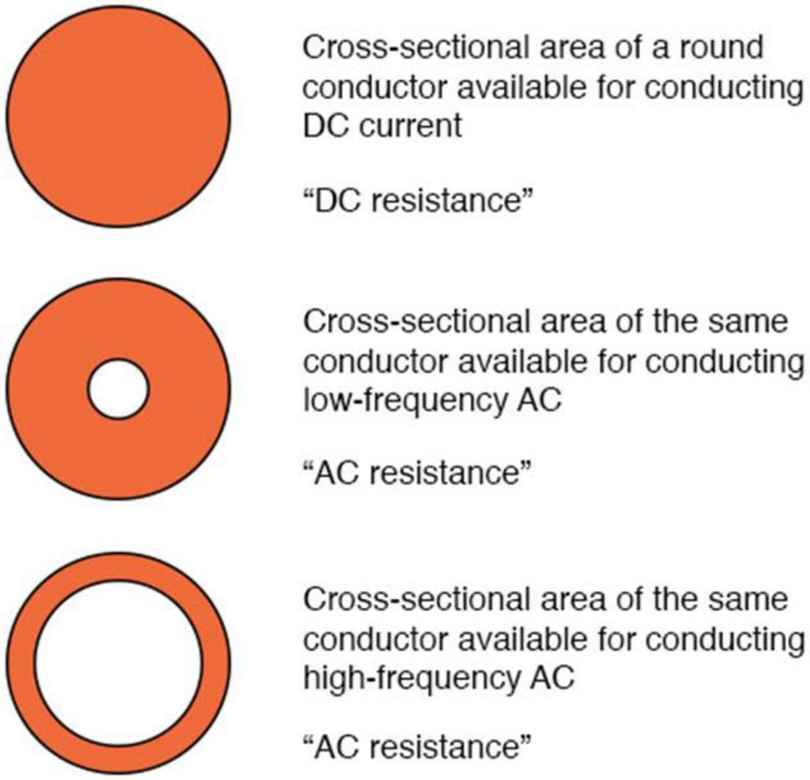

Figure 2.2. Resistance intensity of DC, low-frequency AC, and high-frequency AC in skin effect factor and distribution of current (All About Circuits, 2014).

Four different methods are used to obtain electrical energy in aircraft. The first method is the main generator (MG) which is connected to the gas turbine. Auxiliary power supply unit (APU) that provides energy in an emergency and when the aircraft is in a resting position on the ground. DC network and battery systems that feed the vital systems by converting the stored DC energy to AC thanks to the inverter to meet the direct current (DC) energy requirement that is always required for the aircraft. And finally, it consists of four main components: airflow turbine which is named ram air turbine (RAT) systems that produce enough power for communication, signaling, and some control mechanisms if all energy is exhausted. Now let's examine them in detail.

2.1.1. Tribune Main Generator

Turbine generators are induction generators that meet all electrical energy needs of the aircraft, communication, flight control, passenger entertainment systems, secondary systems (hydraulic, pneumatic, mechanical, and similar) before and during the flight. The demand for electrical energy in today's large-scale aircraft can reach up to 120 kVA instantly (Griffo A., and Jiabin W., 2009). As airplanes have more electrical components and are expected to be much more in the future, existing systems need to be strengthened and new alternative paths must be found, as these innovations and developments pose a huge challenge (Lillo L. et al., 2010; A. Rosero et al., 2007). As a result of these reasons, it is foreseen that the electrical architectural structures of future aircraft will be significant and distinctly different from today's (Griffo A., and Jiabin W., 2009; Ludois D. C. et al., 2014).

When look at the main generator (MG) operating principle, it is seen that the primary power is provided by the jet turbine. Since synchronous induction generators are preferred, a certain value of the input speed must be between toleration. This synchronous speed value is generally designed to be set at 6000 revolutions per minute (RPM) in aircraft generators. This synchronous generator produces an alternating current at constant frequency and voltage at a constant speed and meets the electrical energy demand of the aircraft. While keeping the frequency constant is provided by the constant synchronous speed and a pole number, keeping the voltage constant is kept constant by controlling the rotor flux with a rotor current determined by determining the current load and energy demand (Taneja D. N. et al., 2010).

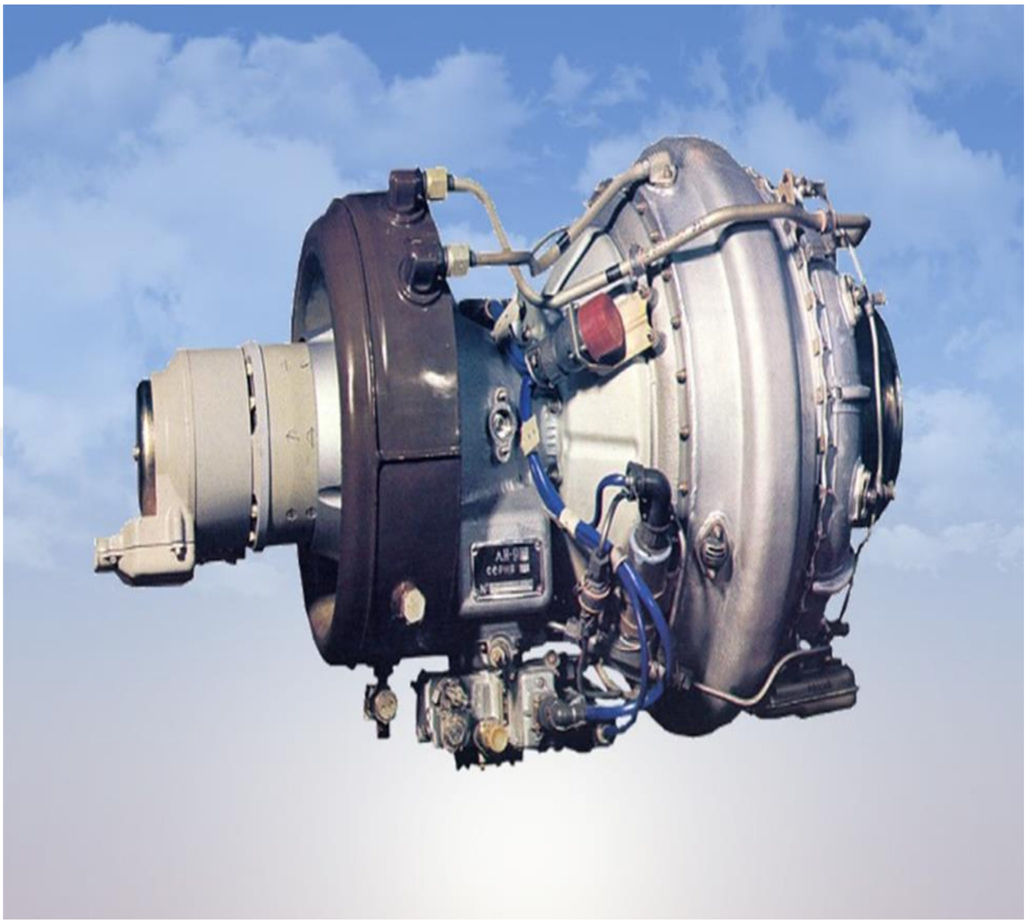

Figure 2.3. Aircraft turbojet engine and main electric generator at the under of tribune.

This picture shows the MG which is connected to the constant speed CSD connected to the turbine which provides the movement and propulsion system of the aircraft. The integrity of the system is shown by converting it to the main generator by converting it to a constant 6000 RPM synchronous output speed according to the hydraulic oil flow or gear system within the revolving speed (average 5000-30.000 RPM) received from the jet turbine engine which varies depending on the flight and atmospheric conditions of the aircraft.

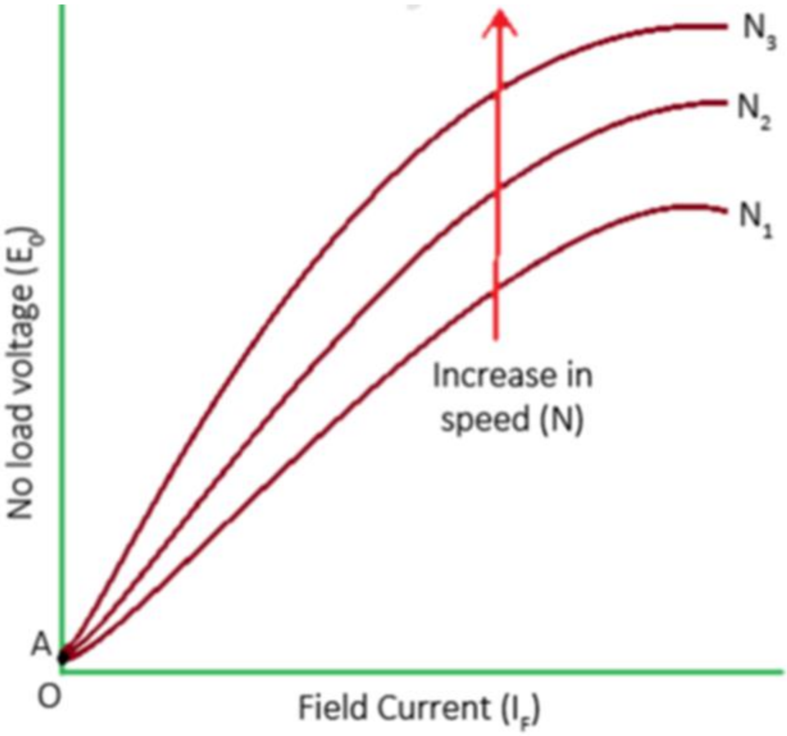

Figure 2.4. For a synchronous generator; no-load and open-circuit stator voltage change graph for different field current at the same speed and the same field current at different speeds.

The figure 2.7 illustaretes voltage-induction mechanism of the variable magnetic field, which is based entirely on the Lenz Law, concerning the speed and intensity of change as it passes through closed cycles. When looked at the figure, it is seen that the voltage value to be formed changes in direct proportion with the magnitude of applied field current and rotational speed (M. W. Baldwin, et al., 2014).

$$\varepsilon = -\frac{d\emptyset_B}{dt} \tag{2.2}$$

$$dB = \frac{\mu_{0.I}}{4\pi}\frac{dlxdr}{r^2} \tag{2.3}$$

$$B=\frac{\mu_{0.I}}{4\pi}\iint\frac{dlxdr}{r^2} \quad (2.4)$$

$$\varphi_B = A.B \quad (2.5)$$

As known, the energy obtained from the terminal of an induction generator is mainly related to the mechanical torque which is applied to the rotor shaft. It can be deduced from this that the decrease in the amount of load demanding power under the applied constant torque causes an increase in the voltage and frequency, otherwise the increase in the load amount causes a decrease in the voltage and frequency and this is not desirable for alternating current networks. To prevent this situation and provide a more stable and pure alternating current to the system, the field current switching method is used. The principle here is to measure the stator phase currents through the closed-loop control scheme, to determine the amount of load demanding energy, and to generate the current value sufficient for this load, a magnetic field current value is determined by the closed-loop controller. Thus, the constant mechanical speed and constant voltage constant frequency target in induction machines are achieved.

It is provided by the CSD, which is essential for the operation of this mechanism used in aircraft.

2.1.1.1. Constant Speed Drive (CSD)

This mechanism used in conventional aircraft electric generators can be characterized as a mechanical interface or drive. When it is considered that jet turbine engines that provide thrust and movement to the aircraft are shaped according to the speed of rotation per minute according to flight conditions, such as gaining or losing altitude, gliding or sudden maneuvering movements, it is not possible to provide tolerance such as vehicle gear systems with a simple gear ratio system. Because this rate can vary between 5000-30,000 RPM and can vary continuously and depends entirely on the flight conditions (Moir I. and Allan S., 2011) (Zhao X. et al., 2014). At this point, the CSD must be installed between the jet turbine and the mechanical turbine (Hegner H. J. et al. 1996).

The basic operating principle is an interface that provides a constant and desirable mechanical speed and torque to the output independently of the input speed through mechanical actuators, controllers, and permeable channels that can provide variable oil flux. If the turbine speed increases or the requested electrical load decreases, it reduces the amount of pumped oil and keeps the speed of the rotating gear system constant with 6000 RPM. Conversely, if the turbine speed decreases or the number of electrical load increases, it increases the amount of oil pumped, thereby increasing the total oil flow, maintaining the main generator input shaft speed constant at 6000 RPM.

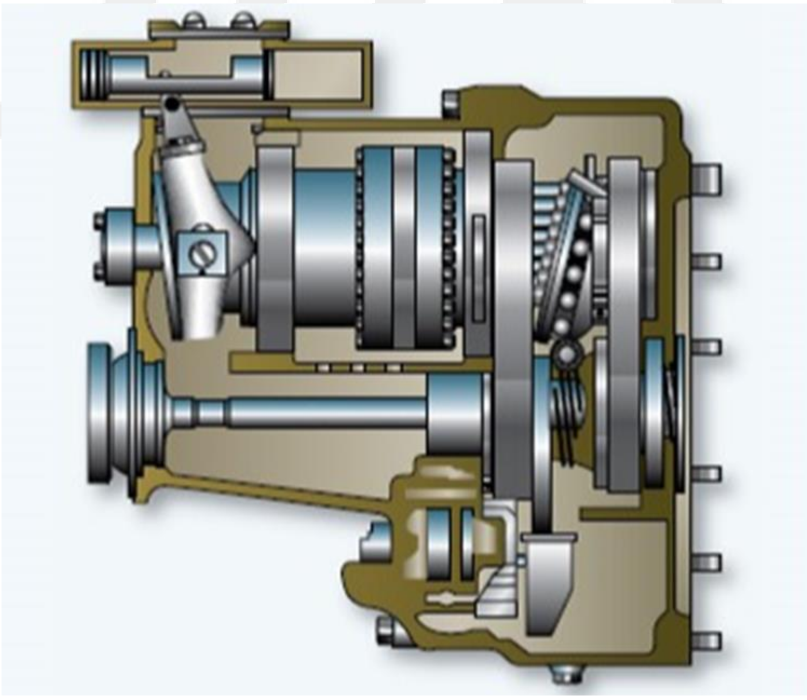

Figure 2.5. Mechanical structure of the CSD system (Flight Mechanic, 2014).

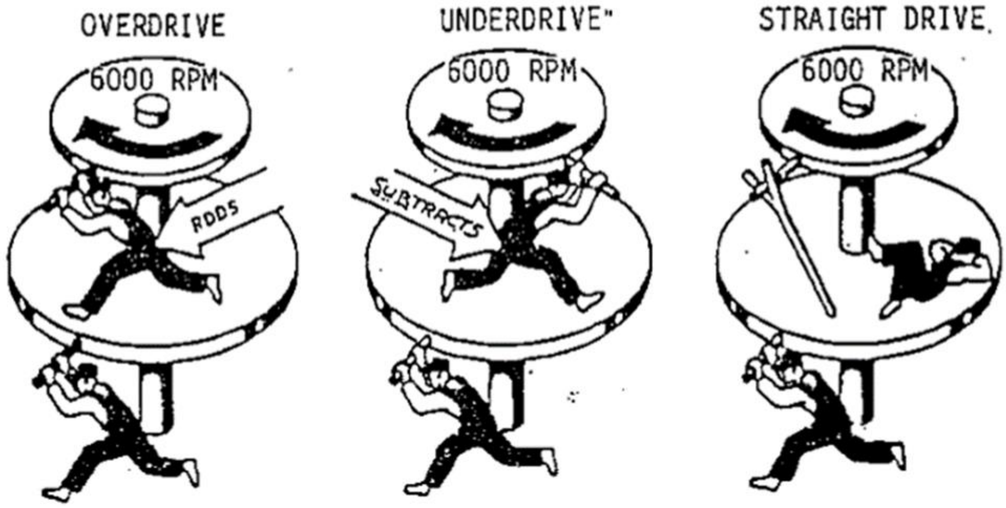

Figure 2.6. A animation showing the CSD working principle at sub-synchronous, super-synchronous, and synchronous rotor speed respectively.

This structure has been the subject of research and development for many years due to its physical weights, volumetric footprint, low and noisy operating characteristics of its efficiency, and frequent maintenance and service. As it continues its development, the search for alternative ways of replacing also raises different research topics.

2.1.1.2. Integrated Driven Generator (IDG)

The system which is obtained by turning the main induction generator into a one-piece block with a constant speed drive system is called an integrated drive generator system. It is a design designed to reduce the physical distance and to reduce weight and increase efficiency by reducing shaft length and to achieve a more compact structure by reducing the occupied volume.

Figure 2.7. Integrated Drive Generator structure, the black part CSD, and the green part of the two are combined into a single block.

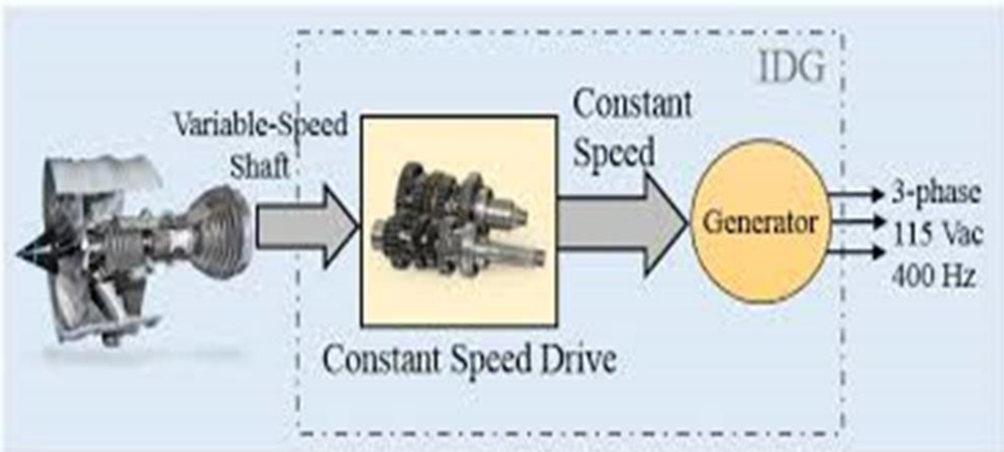

Figure 2.8. This figure shows the transfer of the variable speed taken from the aircraft turbine to CS by fixing it with CSD and as a result the flow of the 3-phase, 400 Hz and 115 V electrical energy system as a single block with IDG (P. Giangrande, et al., 2018).

In this section, investigations and researches have been made on the main generator of the aircraft. The next section will focus on the auxiliary power unit (APU).

2.1.2. Auxiliary Power Unit (APU)

Although the name is an auxiliary power unit, it is a self-propelled, diesel-powered induction generator, which is as important as the main generator, and which manifests itself in many aspects such as controlling the glide rate (GR) and adjusting the range from being able to meet a significant portion of the aircraft's electrical energy demand.

The auxiliary power unit is called the power supply when the airplane is not running or is in motion, in case of a fault in the turbine generators, fixed speed drive or main generator, and in case of failure. Another important task is to provide the necessary energy during the first operation of the jet turbines. As is known, the blades and rotors of aircraft turbines are enormous in weight and require considerable force and energy to give the first movement(Thormann J., et al., 2008). If this system were to be provided with an electric drive motor like in cars, it would be a very big, powerful, and heavy machine. Therefore, the first preferred starting engine in aircraft is a pneumatic air pressure machine. The jet turbine is driven by the high pressure and pulsed air produced by an air pressure compressor connected to the mast of the auxiliary power unit diesel drive motor is thus operated.

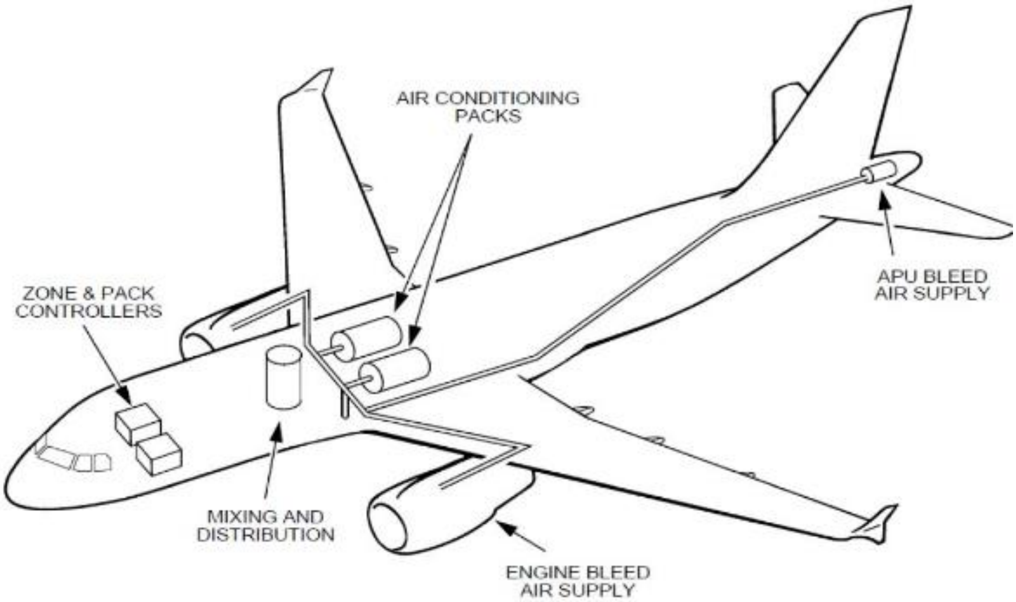

Figure 2.9. Location of the Auxiliary Power Unit and compressed air emission line (Aviation, 2015).

This picture shows the position of the APU system in an aircraft and the transmission and distribution line of the high-pressure air produced by the integrated compressor. Another important issue here is one of the areas where the APU system plays an important role, to allow the aircraft to land with only the glide movement in themevent of a possible fuel run down and to help control this landing. Here, the factor that is called the Glide Rate (GR) comes into play. In average weather, an airplane with a height of 10,000 feet is designed to travel 200 kilometers horizontally, which is determined by the airflow dynamics and the flight and static design of the aircraft (Abdulrahim M. and Lind R. 2004). At this stage, an air inlet window and unidirectional flow valve of the APU are opened, allowing the aircraft to control the airflow and direct the glide(Maldonado M. A. and Korba, G. J., 1999.).

Referring to the position of the APU, it is seen that the aircraft is located in the tail section. The main reasons for this are balancing the center of gravity as a result of more balanced and consistent weight distribution of the aircraft and providing a comfortable and comfortable journey by keeping it away from the cockpit that may occur.

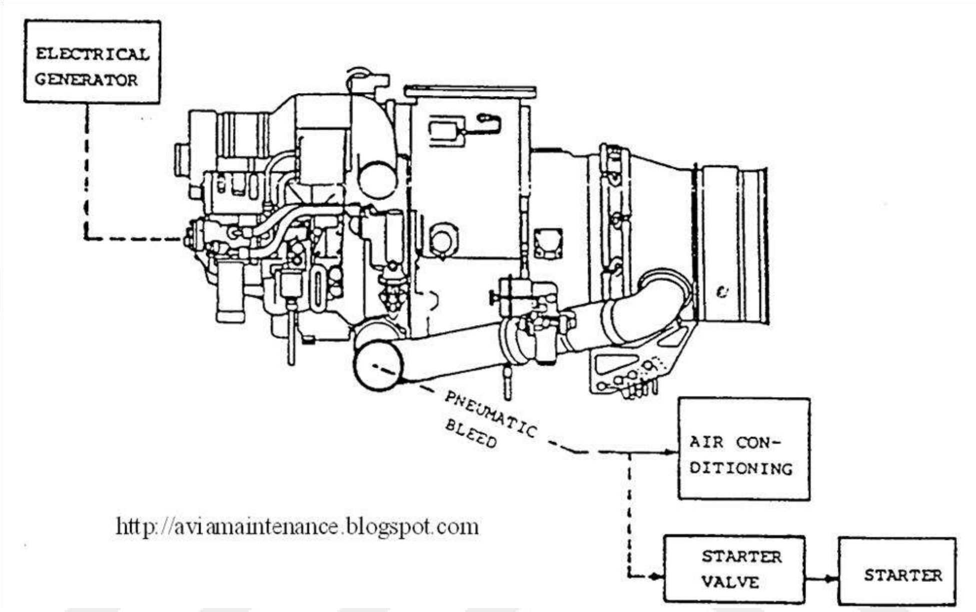

Figure 2.10. General structure of APU, functional aspects, components, and location of components (Yasantha Pathirana, 2011).

The Boeing 747, one of the standards and most well-known aircraft models, includes two 90 kVA main generators as well as an APU of 60 kVA, and it is seen how important the APU system. APU is a self-propelled induction generator system that gains mechanical energy with a four-stroke diesel engine. While the aircraft is resting on the runway, it also supplies the transformer rectifier unit (TRU), which is connected in parallel to the entire AC network, with the 28 V DC energy obtained from it, ensuring that the batteries in the aircraft are always fully charged and that all systems and loads requiring DC energy feeds. Besides, aircraft turbines do not work while air conditioning of the cabin takes on an important task.

Another important feature of this system, which undertakes such important and large operations and fulfills these tasks, although the name is an auxiliary power unit, cannot simultaneously operate the jet turbine and generate full electrical energy at the same time (Sangsefidi Y.,et al., 2012). Because of the compressed air to be applied to operate the turbines must have very high pressure and energy. And it is extremely challenging for the drive motor to produce both full-level electrical energy and the required compressed air at the same time, so the power generation capacity is reduced to a minimum.

Figure 2.11. Position of a conventional Airbus A320 in the auxiliary power unit and tail section (Wikipedia, 2014).

After the normal operation of the aircraft turbine engines, the main generators are also engaged and the electric energy required by the aircraft is started to be obtained from the main generators. After this stage, the auxiliary power unit automatically stops working and goes into rest and becomes passive by being out of the system. The auxiliary power unit is automatically activated only after one or two of the aircraft's turbine engines or main generators fail partially or completely after a non-normal unit condition (Chengwu L. et al., 2002). Since the possibility of the turbine engines to disappear after this stage, the only task it will assume is to produce full level of electricity. Now that the situation is a bit critical, the electrical energy that is consumed by the aircraft when it is needed and which is not of vital importance, such as passenger entertainment system, interior cabin lighting, air conditioning, and air conditioning systems, is more important and vital by disabling the systems, communication, signaling, electro-mechanical control, such as systems (WO Vianna et al., 2011).

Under the title of the Auxiliary Power Unit, it had examined the general structure of the APU system in airplanes, its location, what needs it is used for, and its characteristics as a result of a detailed literature review and comparisons.

2.1.3. Direct Current (DC) Power Systems in Aircraft

Aircraft complex electronic and control systems, electronic and resonance circuits used in components such as BJT, FET, MOSFET, JFET, and most importantly in the event of an emergency that can be stored in the batteries stored in a DC source line is one of the indispensable systems for aircraft. In general, the DC system of aircraft; DC loads consist of inverters and convectors, batteries, and transformer rectifier unit (TRU) (M. J. Provost, 2002).

Transformer Rectifier Unit-TRU: The transformer rectifier unit is a composite consisting of 3 sub-components: transformer, rectifier unit, and a DC filter. The first block transformer reduces the alternating current received by the aircraft from the AC network of 400 V to 115 V, to a lower and reasonable AC value. The next step is the full-wave rectification of this reduced AC power by entering the diode rectifier (R. Bojoi et al. 2012). As a final step, the ripple values of the waves at the peak point are reduced and smooth, and 28 V DC electrical energy is supplied to the aircraft's DC network and used in all the components needed. On the other hand, it is ensured that the standby battery systems are always full (J.A. Rosero et al., 2007). The TRU, the aircraft's DC power source, receives the AC power it needs from the AC mains to which the main generator MG and the auxiliary power unit APU are connected in parallel.

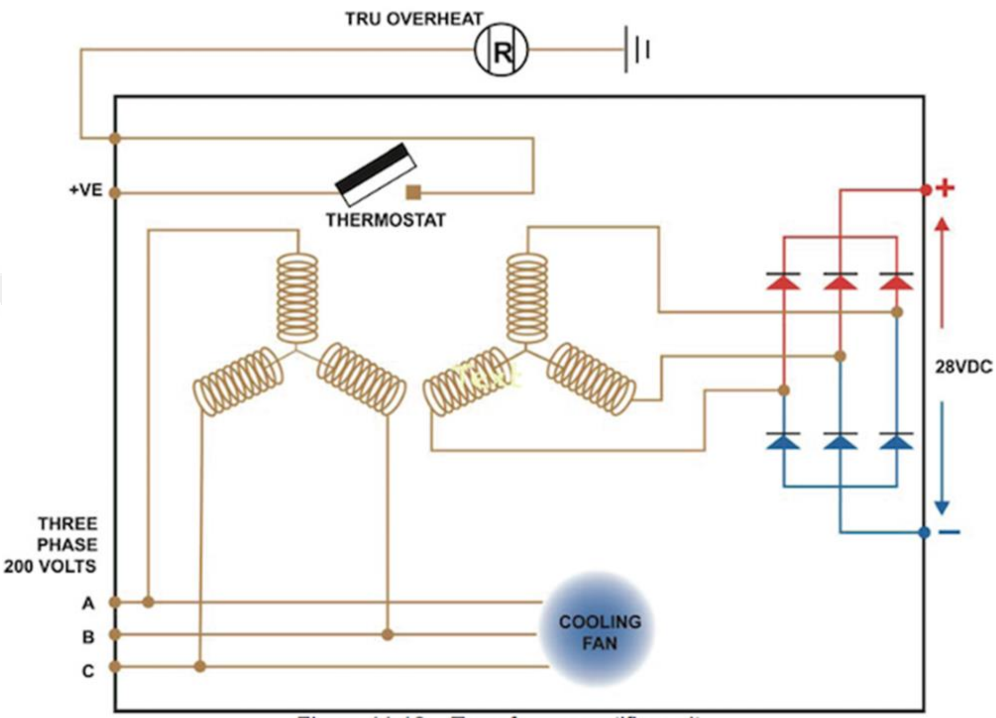

Figure 2.12. TRU diagram with DC power supply for airplanes (Datsen Davies Tharakan, 2018).

Another system that has been used in recent years to obtain DC power in aircraft is another method consisting of 6, 12, or 18 pulses AC-DC converters with automatic transformer rectifier unit (ATRU) (G. Buticchi, 2018). This is to determine the instantaneous total DC power requirement of the aircraft through controllers and to provide the need by performing a pulsed cycle with a switching frequency appropriate to it (LillO L. et al., 2010).

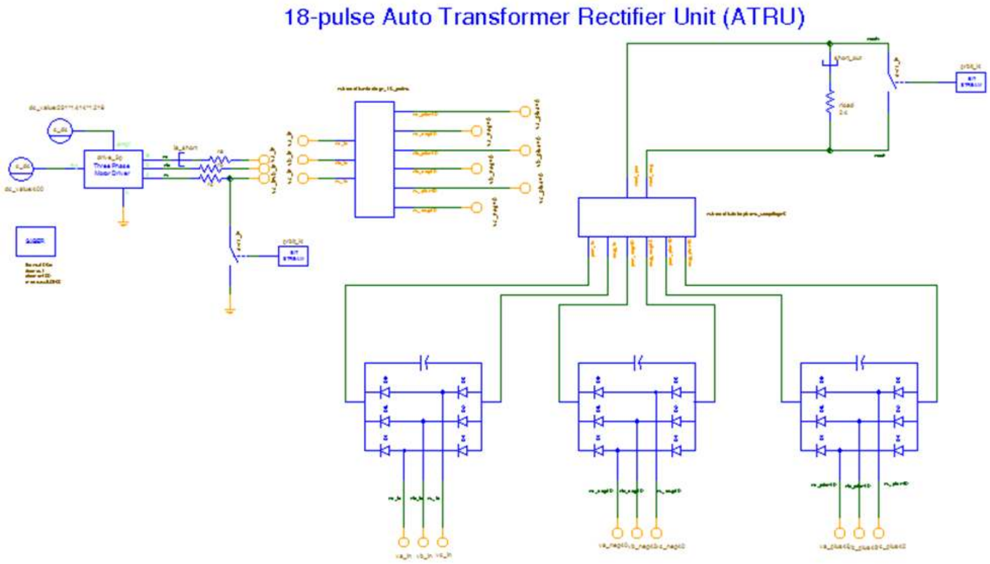

Figure 2.13. 18-pulse automatic transformer rectifier unit model used for DC power needs of aircraft (Bojoi R., 2012).

DC Energy Stored Batteries: Aircraft must always have storage systems to keep energy available, and the systems that can provide these are batteries. Considering the flight conditions, the reliability and low service requirements are as important as the life and capacity of the battery systems that can be used in aircraft (John B. Timmons et al., 2015). For these reasons Ni-Cd (nickel, cadmium) batteries are preferred in aircraft. Other features that should be reliable are the fire and explosion-proof outer layer, which must be protected against leakage of the vapor or liquid form of the acid solution(Rocha N., 2015). In terms of performance, it should be said that many features are suitable for charging and discharging and that the plates do not deform quickly and that they can be charged quickly at the time of charging (John B. Timmons et al., 2015). Besides, they are expected to achieve the expected minimum performance in extremely cold weather at high altitudes (M. Tariq, 2015).

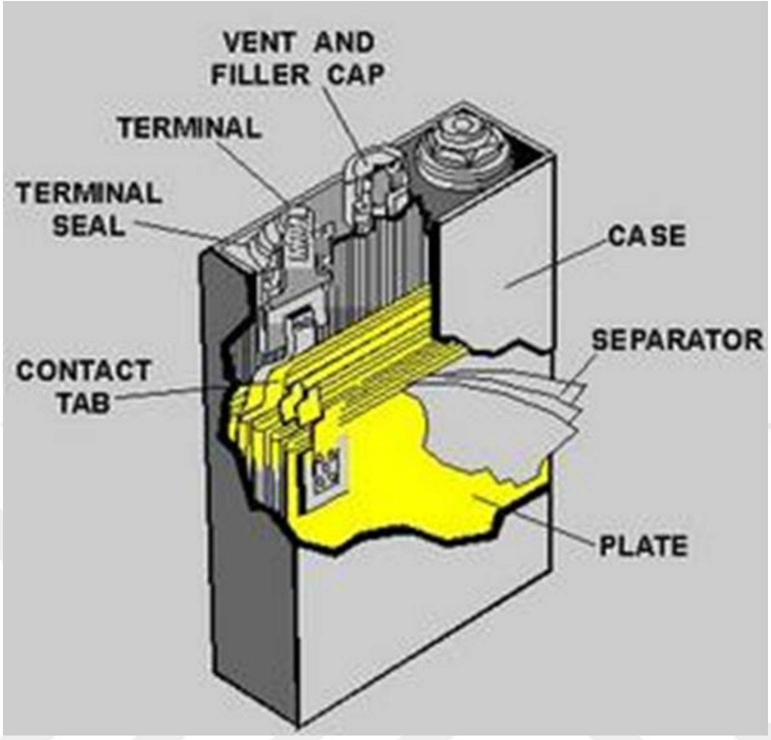

Figure 2.14. Cross-sectional view of the Ni-Cd battery used in aircraft (Wikipedia, 2007).

One of the most important tasks of these batteries is to provide the high current value for starting the electric start motor in a short time to give the initial power to the auxiliary power unit (R. A. Marsh 2001). Failure to perform this function will cause all systems of the aircraft to be de-energized and unable to operate, including the APU and turbine engines.

Figure 2.15. Exterior view of high-performance Ni-Cd batteries used in aircraft.

Types of converter/inverter used in aircraft: The nominal DC voltage in the aircraft network is 28 V. In some electronic circuits this value may need to be lower or higher than 28 V. To meet this requirement, DC-DC buck or DC-DC boost converter is generally used (Simoes M. G., 2007).

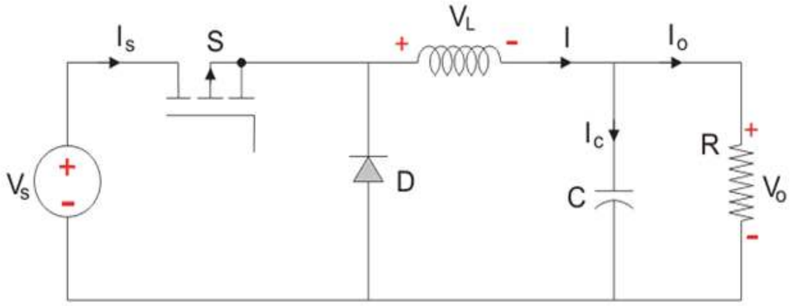

Figure 2.16. Buck (step-down) converter circuit diagram.

$$V_o = \frac{1}{T}\int_0^T v_o(t)dt = \frac{1}{T}\int_0^{DT} v_s(t)dt = V_s.D \quad (2.6)$$

$$(V_{in} - Vout).t_{on} - V_{out}.t_{off} = 0 \quad (2.7)$$

$$\frac{V_{out}}{V_{in}} = \frac{t_{on}}{t_{on}+t_{off}} = D \quad (2.8)$$

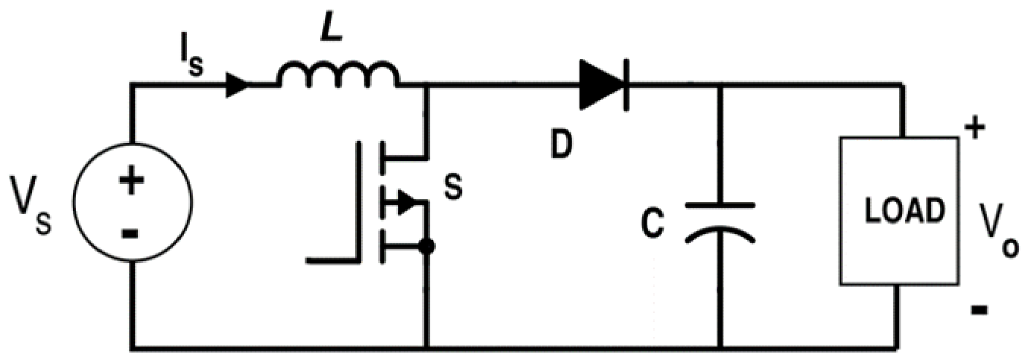

Figure 2.17. Boost (step-up) converter circuit diagram.

$$V_s.(D - 1 - D) - V_0.(1 - D) = 0 \quad (2.9)$$

$$V_0 = \frac{V_s}{1-D} \quad (2.10)$$

When MG and APU systems, which are the marginal electrical energy source of aircraft, lose their ability to produce energy, they can be used to feed vital systems by converting the DC electrical energy already stored in batteries to AC power with the help of inverter (Evgeni G., et al., 2011).

Figure 2.18. Static aircraft inverter system.

2.1.4. Emergency Generator Ram Air Turbine (RAT)

Finally, when it is considered about the system that meets the electrical energy needs of the aircraft in the most recent and most demanding conditions, it is seen the air winter turbine systems (Shanshui Y., et al., 2012). The RAT is an induction generator with one under each wing of the airplane, which is activated by an automatic switch or manually when all electrical power sources are ineffective in emergency situations, and which is fully powered by the air filtration resulting from the free gliding of the airplane. The power that each can generate is approximately 3.5 kVA and is capable of feeding the vital systems of the aircraft (A. S. Altoma and M. R. H. Alhakeem, 2018).

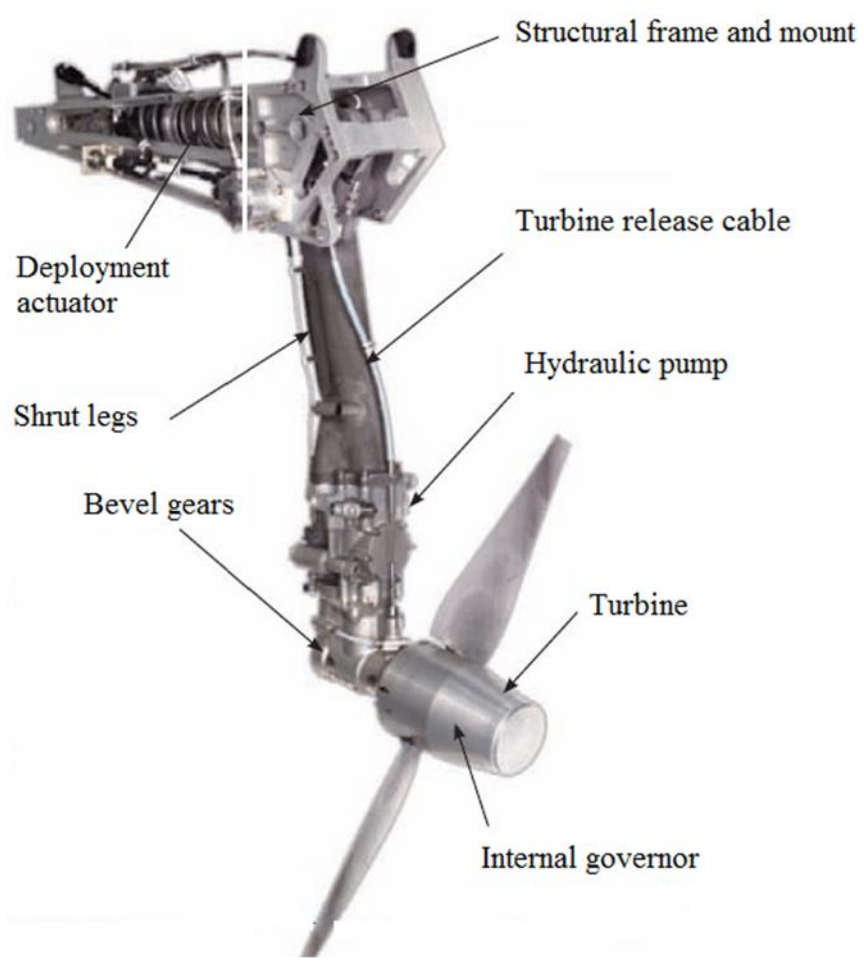

Figure 2.19. The RAT system used in Airbus 320 aircraft and its main components(Cao W., et al., 2012).

Another important task of the RAT system is to control and manage some mechanical systems with the pressurized oil obtained by the oil pump on the shaft. If it is not normally needed, it is hidden and passive in its housing inside the wing. As specific information, Boeing 737-type passenger aircraft are designed to be controlled manually by the pilot when all electrical energy sources are exhausted, so they do not have RAT.

Figure 2.20. Located on a commercial aircraft The RAT mechanism was pulled out during maintenance on the ground (Mark Goertzen, 2016).

In this subsection, electrical energy production and storage methods which are commonly used in aircraft are mentioned one by one. In the next section, how these systems are connected, connection schemes will be discussed.

2.2. Connection Configurations of Aircraft Power Generation Systems

When looked at the electric power generation pathways of the plane mentioned in the previous sections, it is seen that the plane includes a DC and an AC power line. Although each of these systems has its operating system and characteristics, as a result the whole electrical energy system of the aircraft is connected, there must be a certain connection diagram and arrangement between them.

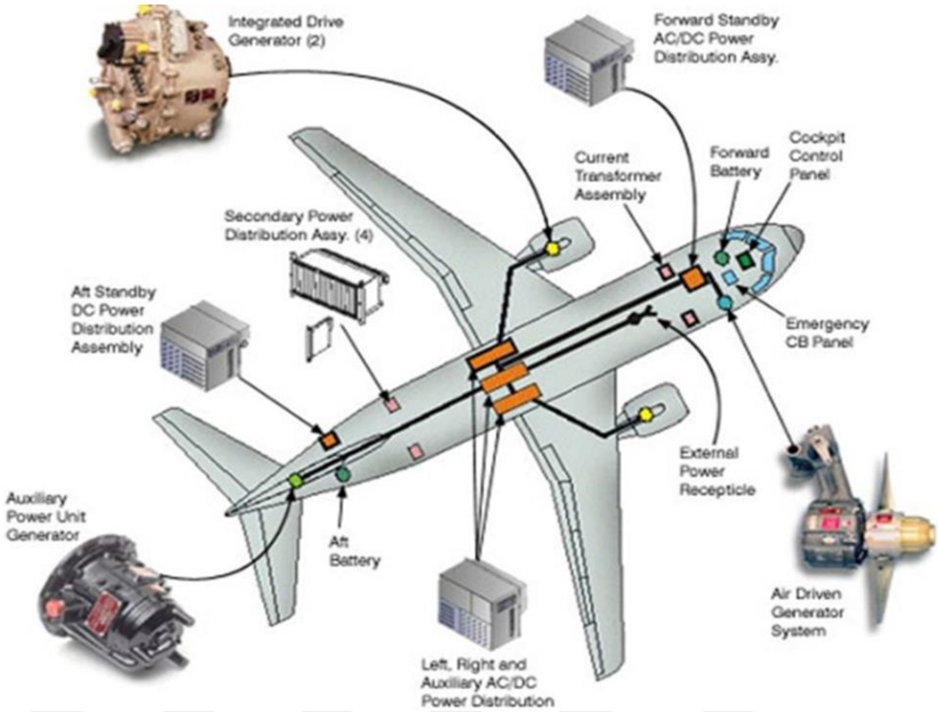

Figure 2.21. Basic connection method of AC and DC source and transmission paths of aircraft (Chester Mosley, 2015).

2.2.1. Aircraft AC Power System Connection

In light of the research topics mentioned above, it is learned and saw that the main AC power sources of the aircraft are MG and APU. Airplanes generally have two separate channel AC bus bars, which connect on a common mainline. The main purpose is to make it possible to provide this deficiency through the main bus bar via the other main generator or APU when one of the bus bar lines that supply the individual systems fails or weakens.

In the event of a possible main generator failure, there will be a serious loss of energy on the respective bus bar and consequently the need. In this case, this need is met by increasing the energy generated by the other main generator and by re-commissioning the APU if it is insufficient. At the same time, there is one TRU for each bus bar and the main bus bar, and there are also two interconnected DC buses.

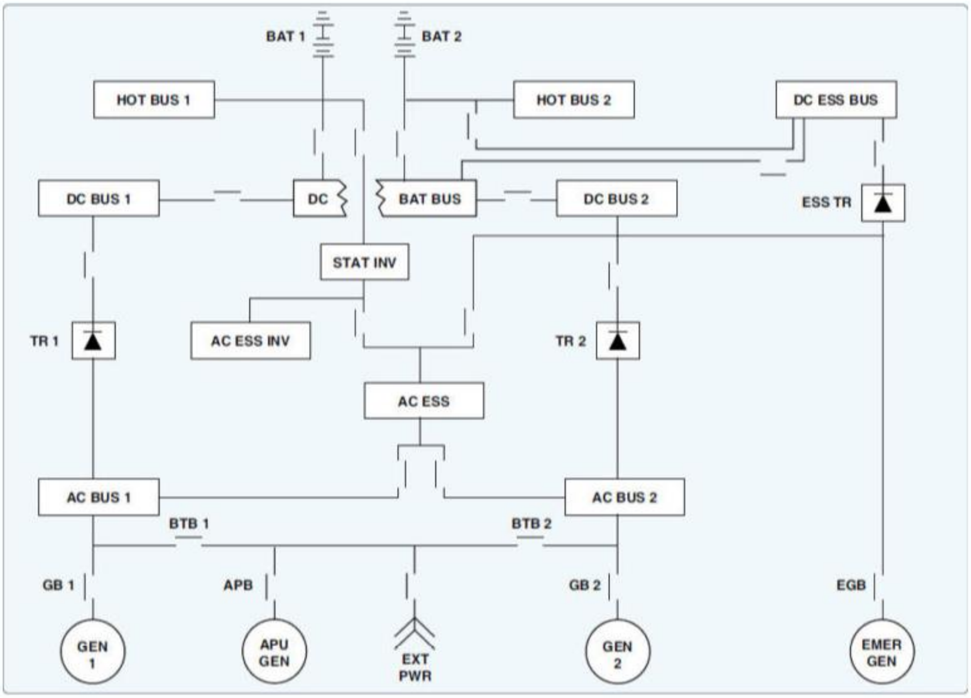

Figure 2.22. Electrical network of aircraft, showing the entire DC and AC production, storage, and distribution diagram (Flihgt Mechanic, 2018).

2.2.2. DC Power System in Aircraft

DC power, which receives input power from the 115 V 400 Hz AC network via TRU and is stored in specially manufactured high-performance batteries, has a very important place in terms of the electrical energy to be stored for the aircraft's DC systems and emergencies. The DC power system, which is based on TRU and batteries, also consists of several sub-transmission lines and a main transmission line and batteries located at several points.

2.3. Other Methods Used in Aircraft Electrical System

The system it has mentioned so far is a widely used constant speed constant frequency and voltage (CSCFV) method which is widely accepted in the world. It is a system designed to produce alternating current (AC) at a constant frequency and voltage according to need with variable field current and shaft torque with a constant speed mechanical speed to asynchronous induction generator.

Although it is not very common, there are some other electricity generation methods used in some commercial and military aircraft besides this method. The most common of these are 270 V high voltage direct current (HVDC) and variable speed variable frequency AC systems. When looked at the disadvantages, it is seen why these systems are not preferred.

2.3.1. High Voltage DC (HVDC)

The basic logic of this system is based on obtaining a voltage of 270 V DC through the AC-DC converter by reducing the AC power at the variable frequency and voltage value obtained from the main generators connected to turbine engines to a certain level by transformer bitterness (J. Brombach et al., 2012). This obtained DC power is supplied to the direct current power line of the aircraft and energy is dissipated. This type of aircraft, which has a very advanced battery storage system, is advantageous in terms of energy that they can store large amounts in case of emergency. Another advantage is that by converting the AC energy it can produce at every revolution to the DC energy through controllers and converters, CSCF is eliminated and CSD is eliminated.

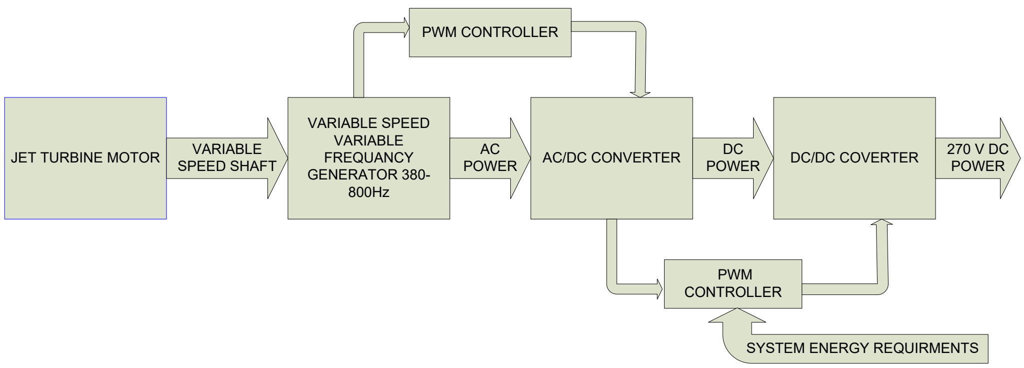

Figure 2.23. Block diagram flow chart of the HVDC system.

The disadvantage is that it contains a large number of converters and inverters. The low energy efficiency of these systems and the high-frequency switching process cause a lot of noise and harmonics. Besides, the thicker conductor cross-section required also entails a physical weight and material burden, and the high energy loss, which is characteristic of DC transmission, is also seen as another disadvantage.

2.3.2. Variable Speed Variable Frequency AC (VSVFAC)

In this system, the speed of the turbine generator is reduced to a certain rate through a simple gearbox and the AC generator is provided with variable frequency and voltage value between 360-800 Hz (J. Li et al., 2018). This system was tested using the Boeing 787. It is also advantageous that these generators are also used as a starter motor for the turbine generator in the first operation.

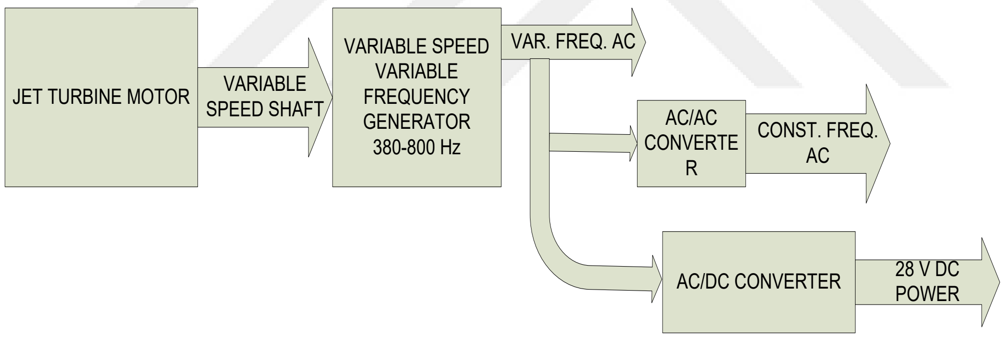

Figure 2.24. Energy flow block diagram of the VSVF AC system.

Because only turbines can rotate at different speeds, it is not possible to connect these two generators producing AC at different frequencies in parallel. For this reason, there must be a separate bus bar for each generator and this is a major disadvantage. Besides, increasing AC impedance at high frequencies causes a higher voltage drop and increased unbalance in the phases. It is a system that is not preferred for these reasons.

2.3.3. Variable Speed Constant Frequency Converter (VSCF with Converter)

Although this system achieves constant output from variable speed but in fact, firstly it obtains an AC energy according to the variable speed then the desired fixed output is obtained with an AC-AC converter. So the working principle of this system is less efficient and complex than the desired topology(M. J. Zandzadeh, et al., 2012).

The parameters of AC energy in the variable frequency and voltage value obtained are firstly calculated with the closed-loop controller and this value is converted to DC power at a certain value(El-Kishky H., et al., 2011). On the other hand, the electrical demand of the whole aircraft is calculated. Through the control signals generated by the parameters obtained from this, the desired 400 Hz 115 V voltage is obtained from the terminal by triggering the PWM module having a high frequency switching feature by the signals obtained by the controller (Mirecki A. et al., 2011).

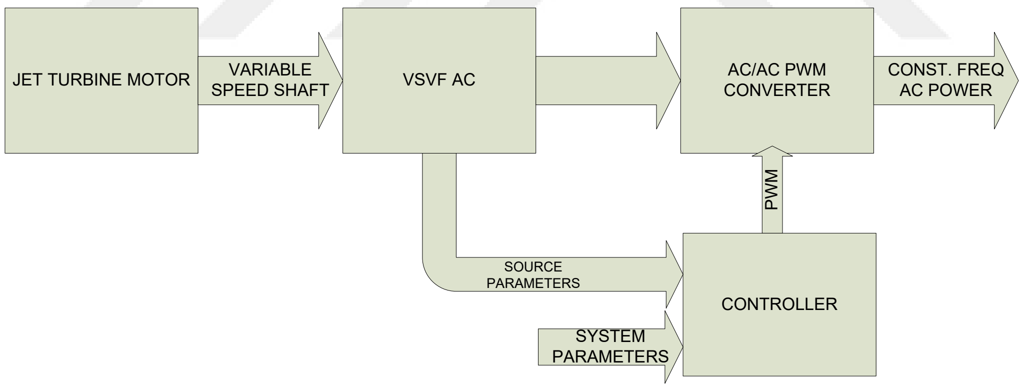

Figure 2.25. Energy flow block diagram of the VSCF system provided with a converter.

Advantageously, a simple gearbox can also be used to generate AC power at variable speeds without the need for a rotating energy CSD system. On the other hand, it is a major disadvantage that a large number of controllers are used, the high speed switching PWM creates harmonic and interference, and the need for frequent service and maintenance due to the sensitivity of the electronic controller cards. Therefore, it is a method used as research and development in some applications rather than being preferred systems.

2.4. Summary

In this section development of airplanes in the light of the changes and developments are worked and research. It has been seen how electrical needs increase as aircraft develop, and it becomes imperative to develop and implement different methods. In the following sections, considering about how to achieve the goal of CSCF, which is the most commonly used aircraft in today's airplanes, the ways and methods which is obtained electrical energy in airplanes, how they are connected between different units and how they interact with each other. Lastly, comparing the methods of electric power generation which are used in limited amounts in airplanes today with comparisons, advantages, and disadvantages and thus it has conducted a comprehensive knowledge and literature review about the electrical systems of aircraft.

3. GENERAL STRUCTURE AND CONTROL OF DFIG AND OTHER GENERATOR TYPES

3.1. Wind Energy and Electricity Generation from Wind Turbines

Looking from history to the present, wind energy is a renewable and unrestricted type of energy source that has been used in many applications throughout the historical process of humanity and has been preferred in many applications and is accessible in many parts of the world. The winds, the formation of which is the mass-energy flow between thermodynamic and pressure centers due to the daily, monthly, seasonal and annual climatic and temperature balances of the world, offer unlimited energy to human beings.

Wind energy, which has been used in numerous applications such as extraction of water from wells, primitive elevator systems, grinding of grains, and processing of crushed metal, has provided many innovations to man and overcome the difficulties. The increasing need for electricity generation due to developing technology and increasing human needs has made it inevitable to tend to cheap, innovative environmentalists and renewable energy sources.

Increasing energy demands in the world, increasingly polluting environment and deteriorating natural equilibrium as a result of a more stringent structure of environmental specifications and laws, increasing prices and fossil fuels gradually increasing to full exhaustion, the search for renewable and environmental alternative energy due to global warming The search for the source has brought wind energy to a very special position (Teow M. Y., et al., 2016). The abundance of wind energy, the amount of potential energy it possesses, and the availability of it in many places have created an intense study on wind energy and open doors for the development of new technologies (Valcan D., et al., 2012).

Methods of generating electricity from wind energy, it is seen that there are many different methods used. It is seen that the main factor of these differences is the type of generator used to generate electrical energy(Rebecca T., et al., 2009).

When looked at the types of generators used mainly in wind turbines, it is seen that synchronous, asynchronous, and direct current generators are used. The main reason for using these different options is the wind characteristics of the region and the amount of energy planned to be produced. Synchronous motors are preferred in the plants where the wind is stable and large amounts of energy can be produced, whereas asynchronous and direct current generators are used in systems where the wind is the less stable and low amount of energy is produced (L. H. Hansen, 2005). In principle, these systems are divided into three categories: CSCF, VSCF and, variable speed variable frequency (VSVF). Now let's have a detailed look at the generator models used in wind turbines and compare them.

3.1.1. DC Generators Used in Wind Turbines

Although their reliability is low and there are disadvantages such as frequent maintenance and service requirements, speed and voltage controls are easy and suitable for systems that will produce small amounts of energy and especially for isolated zone applications make DC generators preferable. Designed with a permanent magnet structure, DC generators convert the generated AC energy to DC energy through diode rectifier circuits. Low power generation capacity is expected to be preferred in systems because the main power of the permanent magnet is limited. The DC energy obtained here can be used directly from the pole and can also be used by converting it to AC energy through the DC-AC converter.

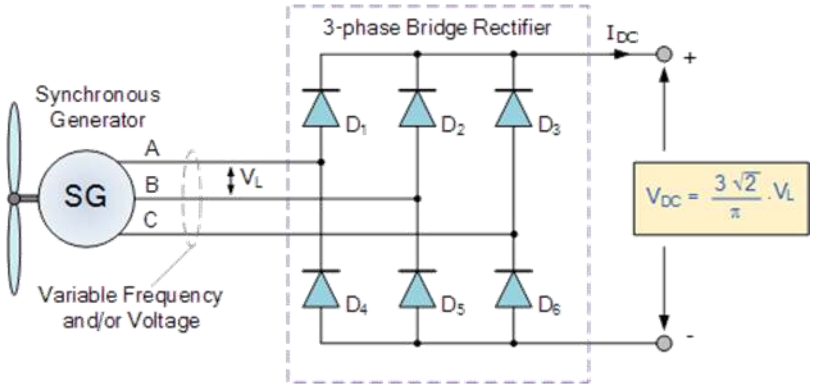

Figure 3.1. Energy flow diagram and diode rectifier diagram in DC generator based wind farm (Alternative Energy Tutorial, 2013).

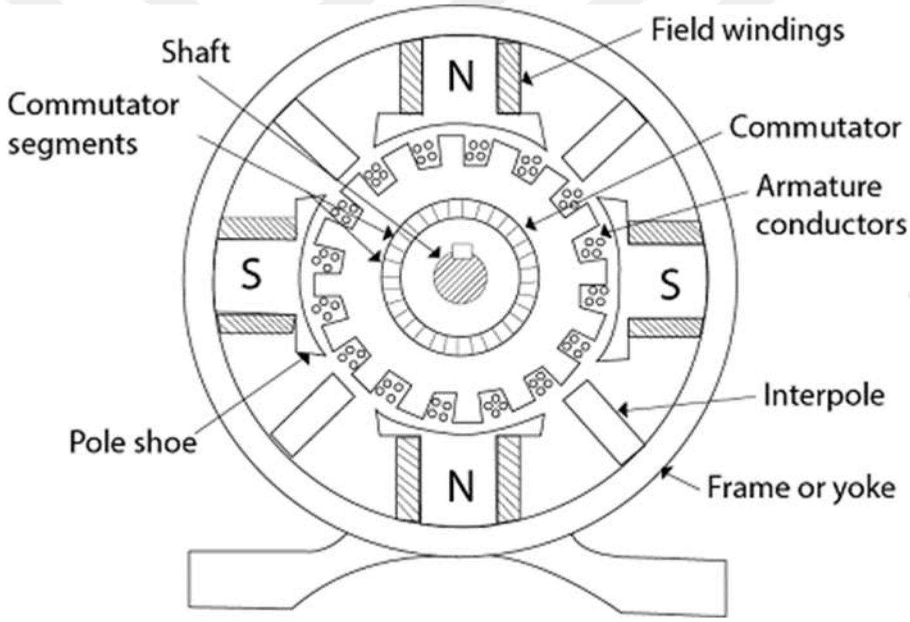

Figure 3.2. DC generator structure and main components (Circuit Globe, 2016).

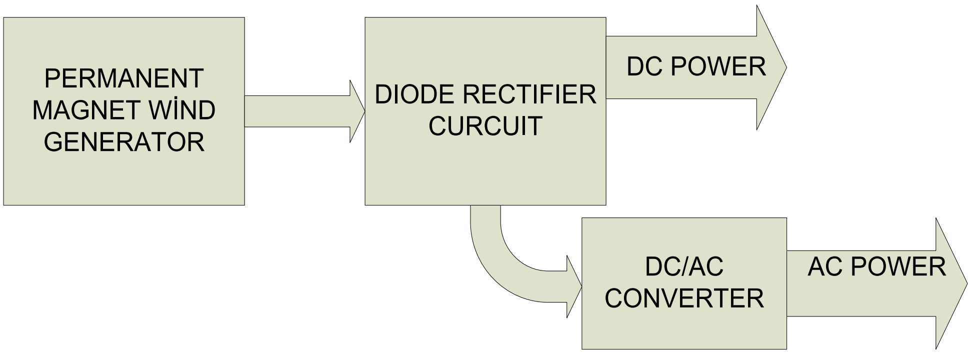

Figure 3.3. Permanent Magnet DC Generator Wind Turbine Energy Flow.

3.1.2. Synchronous Generators Used in Wind Turbines

The synchronous generator consists of a stator formed by three-phase windings supplying an external load and a rotor forming the magnetic field. The magnetic field generated by the rotor is generated from direct current flowing from permanent magnets or windings. Synchronous generators are more suitable for fixed speed systems. Therefore, they operate at a constant frequency depending on the constant speed. Two types of synchronous generators are used in wind turbines, usually, field winded and permanent magnet(I. Nicolae, et al 2014).

Synchronous generators are more expensive and mechanically more complex than induction generators of the same size. The synchronous generator consists of a stator formed from three-phase windings that feed an external load and a rotor forming the magnetic field. Synchronous generators are more suitable for fixed speed systems, which is why their names are synchronous. Therefore, they operate at a constant frequency, depending on the constant speed, with a tolerance of only 3% of tolerance, which can operate below or above the synchronous speed. The magnetic field generated by the rotor is generated from either direct magnets or direct current flowing from windings. The direct current in the synchronous rotors used in wind turbines is provided by the supply from the grid, which is why they are generally preferred in locations where they may already be connected to a strong electrical grid. AC taken from the grid is turned into D.C. It is then transmitted to the windings of the rotor by brushes(H. J. Hegner, et al., 1996).

Rotor Winding Synchronous Generators (RWSG): This synchronous generator model provides the current needed to generate the magnetic field needed for induction by taking DC from the rotor. The stator winding is connected to the network via a four-zone power converter, which consists of two back-to-back voltage-driven inverters capable of switching according to the wave width modulation (PWM) technique. The stator-side converter determines the electromagnetic torque, while the mains-side converter controls active and reactive power. Since the entire stator current is used in the production of electromagnetic torque, the efficiency of this machine is generally high. The presence of a winding circuit in the rotor is a disadvantage compared to the permanent magnet synchronous generator (PMSG). Besides, to regulate the active and reactive power produced, a converter of 1.2 times the nominal wind power must be used and the need to be connected to a strong network is considered as a separate disadvantage (M. Uyar et al., 2008).

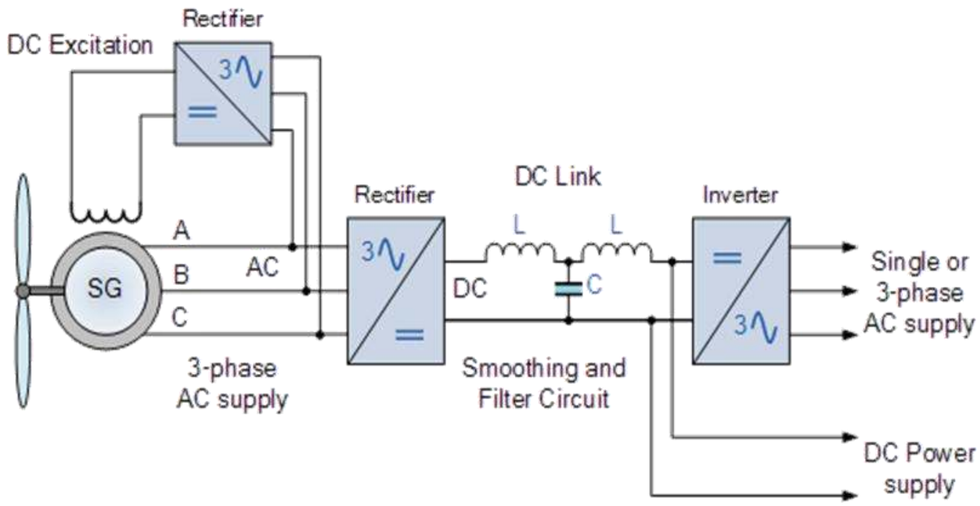

Figure 3.4. Field winded secondary generator (FWSG) for wind turbines.

PMSG: This system, which is preferred for smaller applications and limited electric power generation for isolated areas, is based on the induction of AC in the stator by vector magnetic flux change caused by the rotation of the natural permanent magnet in its rotor. Since it is a permanent magnet, it is preferred because it does not need any current to generate any magnetic field and induces current at every speed. Here, the amplifier DA-DA chopper controls the electromagnetic torque. In addition to controlling the power factor of the input, the converter on the side of the main also regulates the DA link voltage. Generally, this configuration is preferred for wind power systems smaller than 50 kVA.

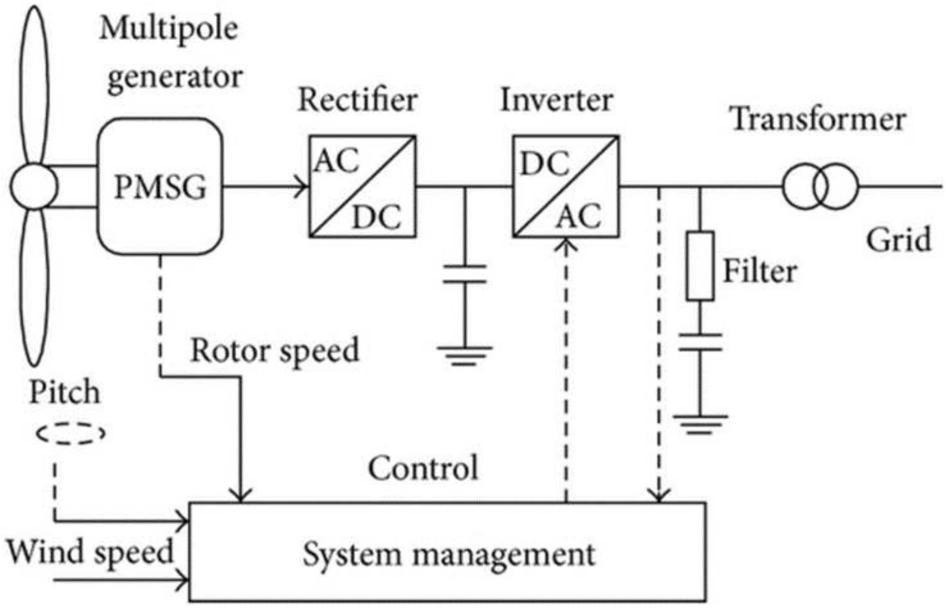

Figure 3.5. Permanent Magnet Synchronous Generator wind turbine configuration (C. Wang, et al. 2014).

The advantages of the PMSG system include the ability to generate power at any speed, low maintenance costs, and low maintenance requirements, and no need to have any networks at the locations where they will generate energy.

On the other hand, the disadvantage of PMSG is that the permanent magnets that make up the magnetic field of the machine are expensive and the magnetic flux intensities may decrease in time and the magnetic flux intensities may decrease, ripple formation of diode rectifiers increasing the amplitude of the current, and most importantly the reflection of the power factor of the machine to the control.

3.1.3. Asynchronous Generators

Due to its robustness, simplicity, efficiency, and cost-effectiveness, it has become a preferred generator type in wind turbines in recent years. Due to its ability to benefit from the vast majority of the wind and not only depend on pitch and yaw mechanical control, but the energy conversion efficiency is also high and thanks to this feature, it can tolerate sudden fluctuations in wind speed. One of the major disadvantages is the need for the reactive magnetization energy required by the stator (American Wind Energy Association Homepage). The squirrel cage asynchronous generator (SCAG) and the rotor winding asynchronous generator (RWAG) are divided into two main classes, while the RWAG is divided into two sub-classes: DFIG.

Squirrel Cage Asynchronous Generator (SCAG): SCAG is used in both fixed-speed wind turbines and variable speed wind turbines. To reduce magnetic noise and interference, and to obtain a good initial starting momentum, the rotor grooves are sloped rather than parallel to the shaft to produce a compressed aluminum die-cast rotor winding, which is due to its ability to tolerate magnetic noise. Squirrel cage asynchronous machines, brushless, reliable, economic and robust structure because they are used frequently in practice.

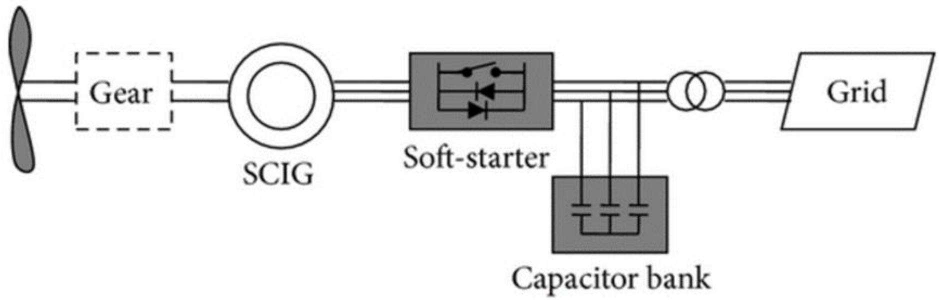

Figure 3.6. Configuration of the wind-driven SCAG system with a simple gear system (Miret D., et al. 2014).

When looked at its disadvantages, the control of the system is complicated by changing the generator parameters depending on the temperature and frequency. Since the torque-speed curve is linear, fluctuations in wind power directly affect the grid. These transitions create a critical situation, especially during the network connection of the wind turbine. At these points 7-8 times faster and greater current transfer than nominal current is a very important disadvantage for the system. Besides, the squirrel cage induction generator consumes reactive power. In many cases, especially in large turbines and weak networks this is undesirable. Therefore, the reactive power consumption of the squirrel cage induction generator is almost always balanced by compensating partially or completely by the capacitors used to bring the power factor close to one (Wind Power Generators in the United Kingdom).

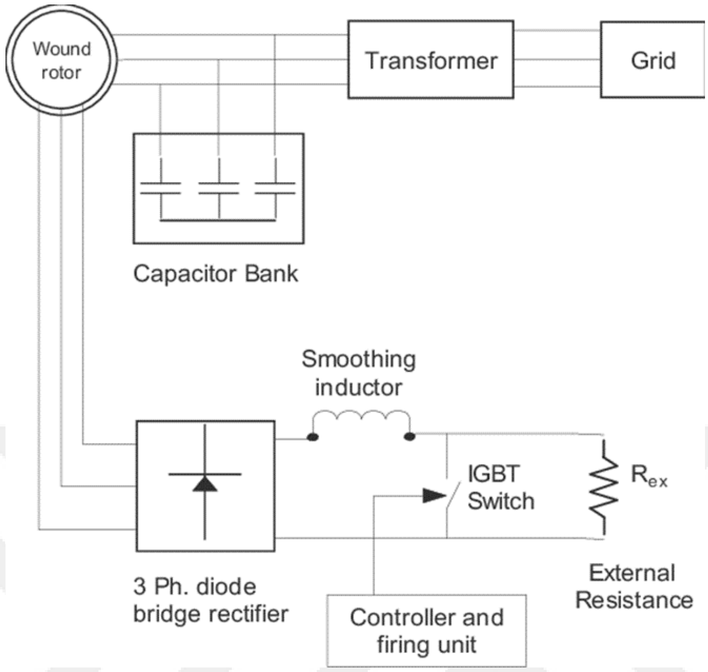

Figure 3.7. Opti Slip Asynchronous Generator used to control the external resistance part and network connection configuration (K. Vinothkumar and Selvan M. P. 2008).

Double-Fed Induction Generator (DFIG): Double-fed asynchronous induction generators system, which is the most popular and popular generator system of recent years in wind turbines, is connected to the grid only by transformer without power electronic circuit on the stator side, stable within a speed frame of 40% and + 40% of a selected mechanical speed and reliable energy. Since DFIG has an inverter that feeds the rotor only through PWM, the inverter can be managed with a maximum inverter power of 25% of the rated generator power. This minimizes the energy losses and the harmonic amount generated by the inverter. This system provides a fast, reliable, and stable response to external disturbances, such as sudden changing load or shaft rotation speed, and can be re-stabilized in a short time with small tolerances. The main control is provided by the 3-phase field current on the rotor minimizes the need for mechanical control pitch and yaw control. It is a type of asynchronous machine which converts the input mechanical energy into the most efficient and major electrical energy as the least affected system by the wind speed within its nominal power limits (Nicolae I., et al., 2014).

DFIG system, which can work with various self-propulsion systems in isolated regions, has recently become an attractive choice and a new field of work for aircraft main generators and isolated diesel generators.

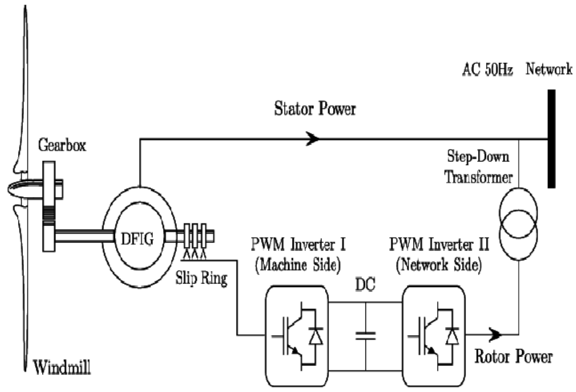

Figure 3.8. Simple configuration of the DFIG system connected to an existing network (B. Babu, et al., 2008).

As shown here, there is an inverter with two divisions, two transducers, and a ripple attenuator that can provide two-way flow. The first transducer on the right, which receives its power from the mains or stator, is called the Stator Side Converter (SSC), whereby DC energy is obtained from AC energy and made smoother through the capacitor. After this, the DC power controller passing to the RSC is shaped according to the PWM waves generated and applied to the rotor. The frequency and voltage of the AC energy obtained from the stator are kept within the tolerance range by this technique.

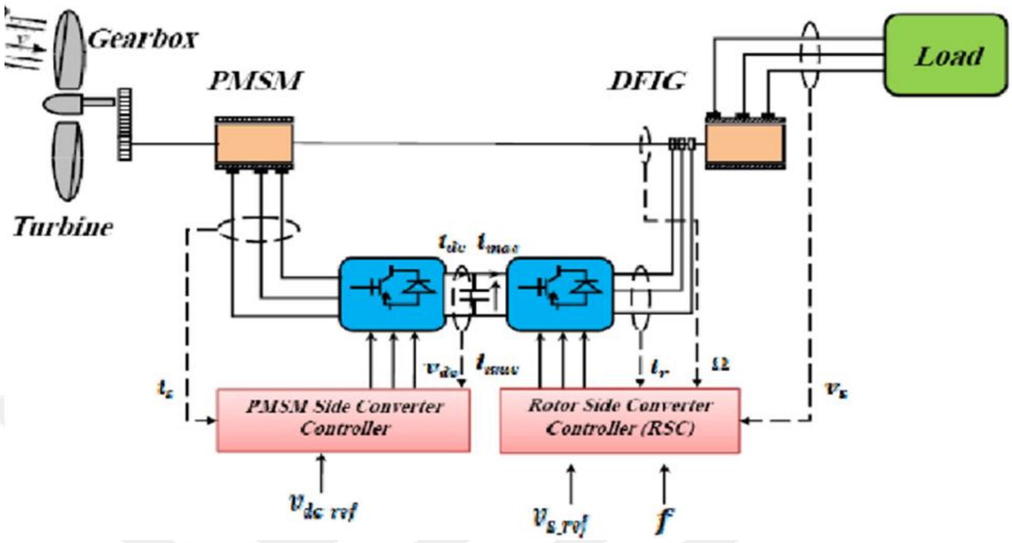

Figure 3.9. Self-propelled DFIG configuration powered by PMSG on the same shaft, operating in the isolated zone (Mezhabi T. et al., 2017).

In this section, it has done a comprehensive and concise study on the purposes of wind energy used today, and in recent history, what are the generators currently used in wind turbines and their characteristics. In the last part, it has mentioned the general structure of the aircraft main generators which are the starting point of our study and the DFIG system which is the source of motivation for this. In the following sections, it will presented our studies on DFIG characteristics, stability equations, control schemes and methods in detail.

3.2. Doubly-Fed Induction Generator (DFIG)

In the previous section, it has examined in detail in the systems obtained from electrical energy from wind energy, which has been going on for many years and tried various systems, it has seen the classifications, advantages, and disadvantages in the classes and the advantages and disadvantages in themselves. In setting up a wind energy field, the climate wind regime and its climatic characteristics, the amount of energy demanded, and the path of the wind is established. But on the other hand, increasing and increasing specifications, laws on the other hand, and it is expected to be renewable energy, can be used effectively and efficiently can be effective from these facilities, as close to as much time as possible, high efficiency and has been able to search for as much as standard systems(Arnaltes S., et al., 2018).

It is precisely from this point that it is an effective, efficient and reliable place in nature and as a source of motivation in systems where mechanical input circuits, such as wind power plants, can vary considerably (D. Ramuz et al., 2006; Avery C. R. et al., 2007). To prepare a good understanding of the issue of constant frequency VSCF AC power generation at variable speeds, which is the motivation source of our work position, it is need to know the DFIG mathematical model on the state of the fifth state.

3.2.1. DFIG General Construction and Properties

The DFIG system is undoubtedly the most popular structure of the wind farms due to its ability to utilize a significant amount of wind energy, ease of control and early response and quick elimination of discomfort, sustainability with up to 25% of the nominal maximum power of the system (AD Hansen et al., 2004; AD Hansen et al., 2007.). Based on DFIG, due to its asynchronous structure, which provides a strong sustainability advantage in either completely isolated areas or with strong networks, the rotor is based on the PWM technique by SSC and RSC of the power received from the stator fed circuit(Í. A. Cavalcanti, et al., 2018).

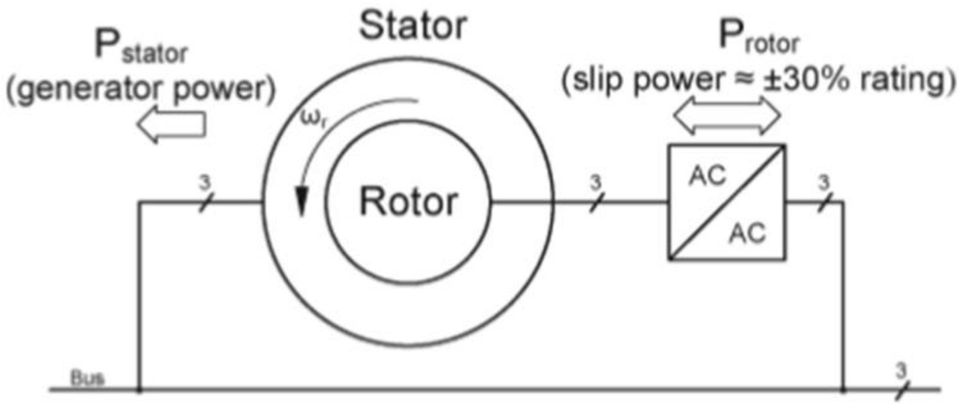

Figure 3.10. Simple and basic view of the DFIG grid connection (Feehally T., and Judith M., 2015).

When looked at the DFIG grid connection shown above, it can seen that the field's current requirement for the magnetic field requirement of the rotor is obtained from the grid through an inverter through bidirectional flow (back to back). The amount of power seen as slip power is the amount of energy that occurs according to whether the system is below, just above or above the selected synchronous speed.

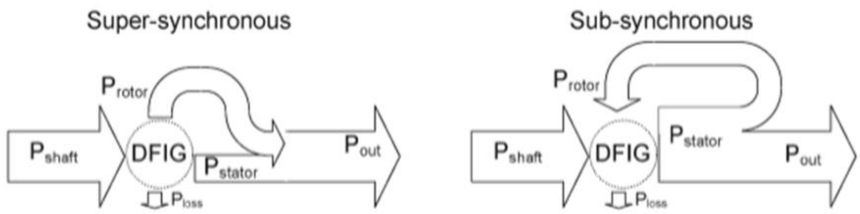

Figure 3.11. Energy flow diagram in super-synchronous and sub-synchronous states (Feehally T., and Judith M., 2015).

When operating in super-synchronous mode, that is the synchronous speed characteristic of the machine, it is seen an energy flow from the rotor to the system. Conversely, when operating in sub-synchronous mode, this time under the asynchronous mode, it is seen that the field current required by the rotor is drawn from the grid. This energy supplied to the grid by the rotor or drawn from the grid by the rotor is proportional to the amount of slip (s) (A. Zohoori, et al., 2012).

$$s = \%(\frac{n_d - n_s}{n_s} X100) \tag{3.1}$$

The amount of slip is indicated as a percentage, and at super-synchronous speeds, the slip is positive (the energy flow from the rotor to the grid), while at the sub-synchronous speeds the slip becomes negative (the energy flow from the grid to the rotor). Here n_s represents the characteristic synchronous speed of the machine and n_d represents the current drive speed (super-synchronous or sub-synchronous) speed. The slip shown as a percentage is also indicated by s. Under super-synchronous mode, slip is positive and under the sub-synchronous mode, slip is negative.

Table 3.1. Data results obtained from the DFIG simulation (T. Feehally and M. Apsley, 2015).

Driven Speed RPM	**600**	**1000**	**1040**	**1400**	**1600**
Slip %	-40	0	+4	+40	+60
Stator Power (% rating)	182	103	100	73	64
Rotor Power (% rating)	-82	-4	0	27	36
Total Electrical Power (% rating)	264	107	100	100	100
Mechanical Power (% rating)	-111	-104	-104	-103	-103
Efficiency %	89	96	96	97	97

Above table shows silip magnitude and sign, stator and rotor rating values, mechanical and electrical total power and efficiency of DFIG due to variable RPM values.

The graph above shows the results of the simulation authors' results obtained from a simulation study for a DFIG request at a frequency of 215 V RMS 50 Hz for a load of 6.6 kW power factor (pf) 1. When looked at the slip value indirectly or directly at the rotational speed, it is seen that the rotor and stator power values change according to the rotational speed, the amount of total electric power generated, and how the efficiency of the system changes. Contrary to expectations, the slip is zero at 1040 RPM, which is slightly higher than the full synchronous speed (1000 RPM). And it is also clear that productivity is increasing with rising speed.

Table 3.2. Data results btained from the DFIG simulation (T. Feehally and M. Apsley, 2015).

Drive Speed (RPM)	600	1000	1040	1400	1600
Slip (%)	-40	0	+4	+40	+60
Real Power (kW)	-5.4	0	0	1.7	2.4
Reactive Power (kVAR)	-3.8	-0.3	0.3	3.0	4.4
Apparent Power (kVA)	6.6	0.3	0.4	3.5	5.0
Apparent Power (% rating)	100	3	6	53	76

This table shows the active and reactive power, apparent power and its rating value due to slip magnitude and RPM,

When looked at this table created from the graphics obtained as a result of the simulation, the reactive power required by the rotor increases at sub-synchronous speeds, while the speed increases, and the reactive power given to the grid increases as the super-synchronous zone moves. While the maximum efficiency of the rotor is observed at 600 RPM which is the lowest speed, the efficiency approaches zero as the speed approaches to the synchronous speed and this point is very close to the synchronous speed, the efficiency increases again as the speed increases.

The general situation it is will understood here is that in a super-synchronous system, the rotor acts as a source, providing energy to the grid to provide the current slip value, and when operating in the sub-synchronous mode, it acts as a consumer by drawing power from the grid to provide the negative slip value. It is a back-to-back converter model that allows bi-directional energy flow (Simões M. G., et al., 2014).

3.2.2. Park and Clark Transformations and direct-quadrature Frame (d-q)

By using these transformations, it is possible to eliminate the parameters that complicate many features of electricity and to create equations that can be studied without complexity in the calculation of voltage and current of the machines. The transformation, also known as the d-q transformation, is expressed in terms of the angle between the rotor axis and the first phase of the stator and modeled mathematically.

The most common way of creating the basic step in providing this control scheme is generally based on the method of utilizing rotor flux. This is the first step where it is necessary to obtain the phase of the rotor flux vector and its amplitude that will transform between the abc and d-q references. The reference current value of the D axis can be obtained against a given flux reference value. The phase angle between the torque and rotor currents can also be used to obtain the rotor torque reference value. The torque difference is obtained by multiplying the speed difference through a PI controller by the appropriate coefficient to obtain the torque reference value.

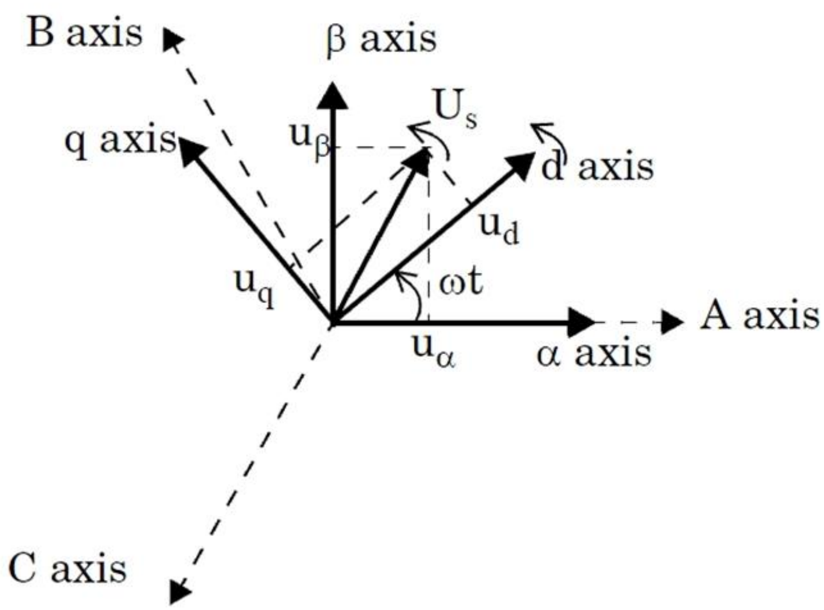

Figure 3.12. d-q reference axis and position of all vector components.

If it is assigned the rotor flux parameter on the d-axis, it is can obtained the block diagram of the d-q model. In flux φ_r: represents the rotor flux, while i_{sd} and i_{sq} represent the components of the stator current on the axis perpendicular to the rotor flow and the stator current. After this modeling, moment τ_r is changed and controlled linearly with i_{sd} , while φ_r is kept constant by keeping it constant with i_{sd}. The current values here are now the equivalent of the actual values in the d-q frame as direct current values.

In the following equation, the relationship, and transformation between the three-phase values v_a, v_b, v_c and V_d and V_q is given (L. J. Ontiveros, et al., 2010).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{2}{3} . \begin{bmatrix} cos\,\theta & sin\,\theta \\ [cos(\theta - \frac{2\mu}{3}) & -sin(\theta - \frac{2\pi}{3})] \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{2\mu}{3}) \end{bmatrix} . \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (3.2)$$

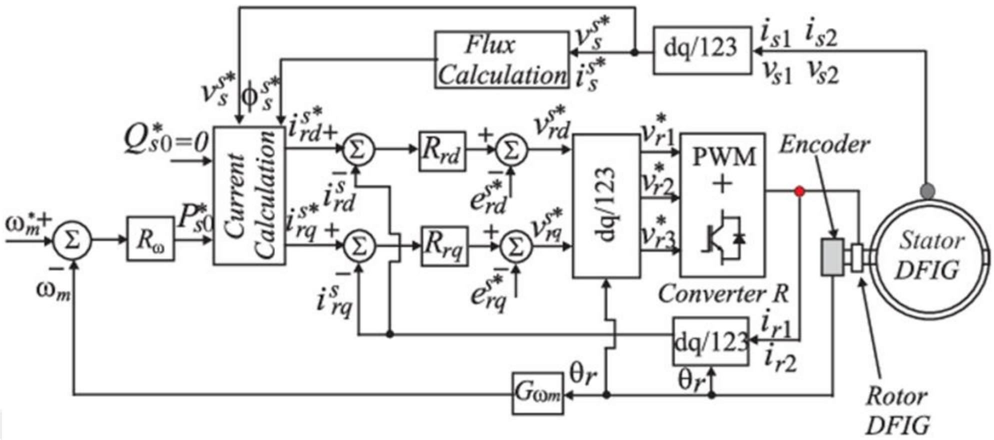

Figure 3.13. The block diagram above shows the encoder connected to the rotor shaft to determine θ_s for vector control of a DFIG system (Italo A., et al., 2018)

3.2.3. DFIG d-q Frame Equations

In this section, it is discussed how d-q frame conversion is performed to facilitate the analysis of three-phase AC generators such as DFIG, which obtains the variable flux in the rotor under variable conditions with the help of PWM converter as a result of the stability equations obtained by PI controllers and sensors.

In three-phase asynchronous generators, stator phase voltages and frequency are kept constant. Due to its asynchronous nature, the rotor must produce a field current of different amplitudes and modulations according to the instantaneous changes and consequently a different parallel field flux. The main determinants of this difference are the variable mechanical rotor speed in the DFIG system and the sudden and significant amount of load changes in stand-alone DFIG systems operated in isolated areas.

The stator and rotor voltage equations for the DFIG d-q frame are given in the following four equations. V_{sd}, V_{sq}, V_{rd} and V_{rq} respectively stator and rotor d and q voltage values φ_{sd}, φ_{sq}, φ_{rd} and φ_{rq} respectively stator and rotor d and q flux components, R_s and R_r respectively, stator and rotor resistors, ω_s synchronous stator speed and ω_r rotor speed and finally i_{sd}, i_{sq}, i_{rd} and i_{rq} respectively stator and rotor d and q represent the current values (K. Abdoune, et al., 2018).

$$V_{sd} = \frac{d}{dt}\varphi_{sd} + R_s . i_{sd} - \omega_s . \varphi_{sq} \quad (3.3)$$

$$V_{sq} = \frac{d}{dt}\varphi_{sq} + R_s . i_{sq} + w_s . \varphi_{sd} \quad (3.4)$$

$$V_{rd} = \frac{d}{dt}\varphi_{rd} + R_r . i_{rd} - \omega_r . \varphi_{rd} \quad (3.5)$$

$$V_{rq} = \frac{d}{dt}\varphi_{rq} + R_r i_{rq} + w_r . \varphi_{rq} \quad (3.6)$$

$$\varphi_{sd} = L_s . i_{sd} + M_{sr} . i_{rd} \quad (3.7)$$

$$\varphi_{sq} = L_s . i_{sq} + M_{sr} . i_{rq} \quad (3.8)$$

$$\varphi_{rd} = L_r . i_{rd} + M_{sr} . i_{sd} \quad (3.9)$$

$$\varphi_{rq} = L_r . i_{rq} + M_{sr} . i_{sq} \quad (3.10)$$

A good selection of the reference values to be assigned to specific positions in this transformation stage may make the analysis easier, and an inaccurate reference selection may make the analysis more complex and difficult. In general, components whose calculation can be directly obtained are not preferred as components to be assigned to the main reference frame, such as stator rotor current or voltage. The terms whose change is determined concerning the other sub-components and indicating the change are assigned to the main axes. The most accurate reference assignment for DFIG is to assign the d axis linearly to the rotor magnetic flux φ_r. The next step is to divide the stator current is into d and q components. While i_{sq} is the component perpendicular to the rotor flux, i_{sq} is the component perpendicular to this current.

3.3. Stand-Alone Operation of DFIG

Considering places far from a strong grid, remote areas, high altitude hills, electrical energy needs are generally met by DC wind turbines or large self-excited (SE) diesel generators. On the other hand, in parallel with the development of self-propelled DFIG systems, widespread use and preference rates of these systems in isolated areas are increasing (A. K. Jain et al., 2008). This system, which can produce AC energy at constant frequency and voltage at variable rotational speed thanks to appropriate control systems, has provided a suitable and applicable system in isolated regions.

The DFIG must be powered by a back-to-back converter, connected to the mains connected to the stator, and must first have a strong, reliable, and sustainable rotor rating. The DFIG system, which is used in areas where there are already strong networks, is first allowed to turn by turning the wing shaft held locked. In general, after starting to rotate, the rotor is allowed to rotate until it achieves a value close to the synchronous speed, allowing it to idle without voltage built-up. Then, after a reasonable rotation speed is achieved, the rotation speed and slip values are calculated through the back-to-back converter, the controllers, a suitable rotor feed is generated by the RSC in the form of the appropriate PWM and the desired magnetic field is created. As a next step, the rotor position sensor determines the frequency position of the rotor and stator and the flow position of the reed series to the same position as the network. And after this stage, the system is connected to the grid, and energy production is realized. During the operation, the control scheme is controlled by the controllers according to the sub-synchronous or super-synchronous speed, as mentioned earlier (N. Patin et al., 2006).

However, this situation becomes different when the transition to isolated areas and brings some difficulties to be overcome. One of the biggest challenges is to provide the energy to perform the first start-up or voltage built-up step, as there is currently no strong grid that can feed the rotor converter circuit in isolated areas. Because this region is already isolated, away from the strong grid, a source is needed to provide initial energy. To provide this initial energy, capacitor banks or battery groups are generally available.

The next challenge is the supply of power to the rotor converter so that the system can operate continuously after the voltage built-up occurs. For this, PMSG is generally used on the same shaft and generates power only to feed the rotor, and another system rarely used is to take the power from the stator output with SSC and drive the power supplied to the RSC after the voltage built-up occurs. Now let's examine these methods in detail and see if they are suitable for adapting them to our system.

3.3.1. Voltage Built-Up of Stand-Alone DFIG

As known, the stand-alone DFIG systems are efficient, reliable and have a strong energy conversion capacity, but the need for the current that generates the magnetic flux that will feed the rotor is the biggest problem (Karakasis N. et al.,2012).

Although the voltage built-up required for the initial start is generally preferred to be within a speed limit close to the synchronous speed, in fact the electricity can be produced within the speed limit that can be produced, within the minimum sub-synchronous and maximum super-synchronous speed. Only at synchronous speed, the system is in standby mode and since the iron losses are minimal, synchronous speed is preferred first.

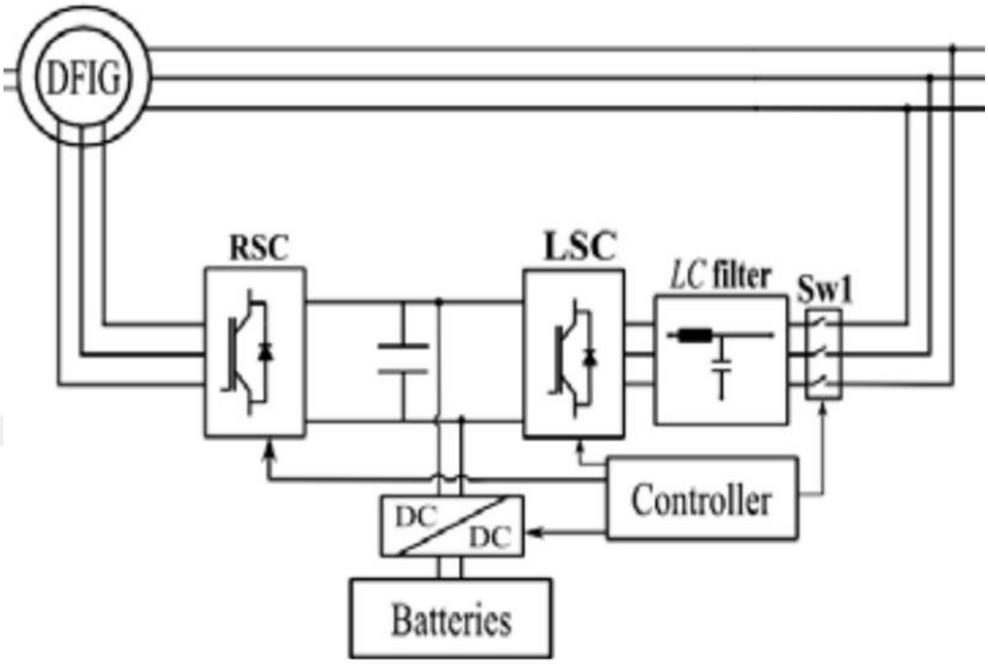

Figure 3.14. Battery connection diagram for the stand-alone DFIG system and voltage built-up.

$$P_{Cu} = R_s\left(i_{ds}^2 + i_{qs}^2\right) + R_r\left(i_{dr}^2 + i_{qr}^2\right) \tag{3.15}$$

The formula for calculating copper losses, the main energy losses for DFIG, is shown above (B. Touaiti, et al., 2015).

$$P_{iron} = c_{Fe_s}(\delta_m w_e)^2 + c_{Fe_r}\delta_m^2(w_e - w_r)^2 \tag{3.16}$$

In the equation here, iron losses, which is also an important loss for DFIG, are given with the coefficients and components to which they are related. c_{Fe_s} and c_{Fe_r} respectively iron loss coefficient for stator and rotor, magnetization axis connection of δ_m, stator and rotor angular velocity of w_e and w_r, and finally $w_s = w_e - w_r$ calculated the value indicates the slip angle. Although the slip factor does not play an important role in the loss of iron, it can cause a serious change in iron losses(B. Touaiti, et al., 2015).

DFIG systems that it is intended to use instead of MG in airplanes show one-to-one similarity with DFIG systems in stand-alone zones, except for the value and frequency of voltage. Another advantage that it can qualified as an advantage is that the energy supply is met by external supply or APU when the planes are in-ground stop mode and they already have a very strong DC transmission line and powerful batteries. This means that the energy required for the initial start-up phase after the jet turbine engines are operational when aircraft are being prepared for off-the-ground flight is superior and there is no need for an extra rotor feed energy system for a start-up. Considering that airplanes often have to make a voltage built-up for MG after each take-off takeoff, it is a great advantage for aircraft to have a large number of supply sources for the start-up phase.

3.3.2. Self-Excited Stand-Alone DFIG

To check something as it has mentioned from the beginning, the two biggest problems of DFAG can be timed to set the current time of the rotor, which is necessary to feed the rotor after the initial phase of the formation of voltage and the start of the operation. After the voltage build-up during the start-up phase was achieved, the two main structures are strong reliable and one of them was used for the rotor. Let's take a look at these structures.

3.3.2.1. Pure Self-Excited Stand-Alone DFIG

The basic logic here is based on the supply of the AC power from the stator to the rotor after the voltage build-up stage has taken place. It has many advantages in terms of lightness, applicability, and simplicity and is suitable for small scale applications, while it has disadvantages such as not being a very reliable structure in large power stand-alone DFIG systems and necessitating continuous strong batteries. In the sub-synchronous mode, where the slip factor is negative, that is, the rotor draws energy from the grid, it can cause system instability and decrease in frequency due to the field current drawn from the grid. To cope with this situation, the power required by the rotor is provided from the batteries provided that it does not take too long to relieve the load of the system. Besides, pitch and yaw control play a significant role in such systems (R. Todd et al., 2009.). By changing the pitch angle, the turbine speed can be increased depending on the angle between the blade and the wind current, thus approaching the synchronous speed to provide the energy needed by the rotor more easily and the slip factor is minimized.

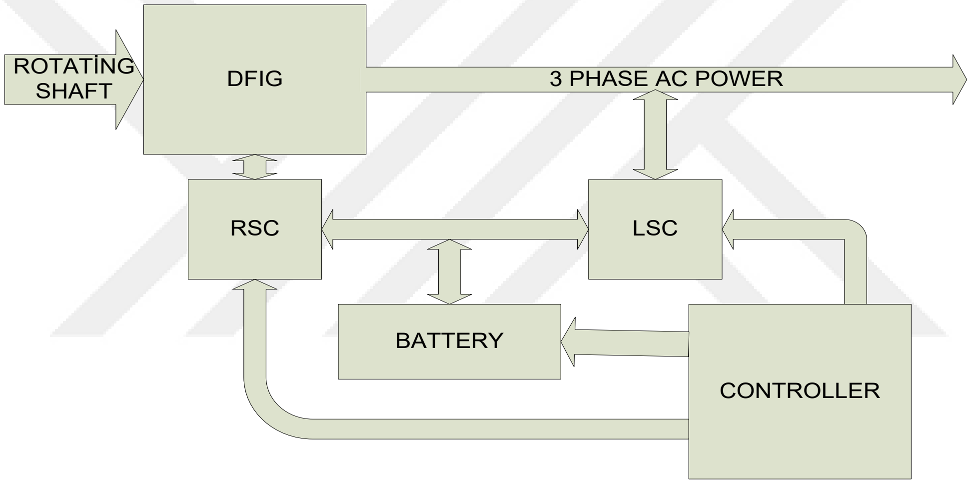

Figure 3.15. Pure self-excited DFIG block diagram connection and control diagram

3.3.2.2. Self-Excited DFIG with PMSM

This system, which is preferred in large-power DFIG applications, comes from a PMSG and DFIG connected in series on the same shaft. Since the DFIG voltage does not go into the built-up phase when the shaft first moves, no power can be obtained from the stator because the rotor current required for the magnetic field has not yet been provided. On the other hand, the PMSG, which is connected to the same shaft, starts to produce energy as soon as it is activated. PMSG produces energy according to the variable magnetic flux principle which is formed by the activation of the permanent magnet in the rotor. The magnetization field strength of the permanent magnet is of a certain constant value depending on its natural structure. This causes a voltage to be induced in the variable flux stator windings that are proportional to the speed of rotation of the magnet. The frequency and amplitude of this voltage depend on the magnetization intensity and the rotational velocity of the natural magnetic material (Pena R., et. Al. 2002.). The variable frequency and amplitude AC energy obtained here is converted into energy close to DC with a slight ripple value with the help of a full-wave diode bridge rectifier.

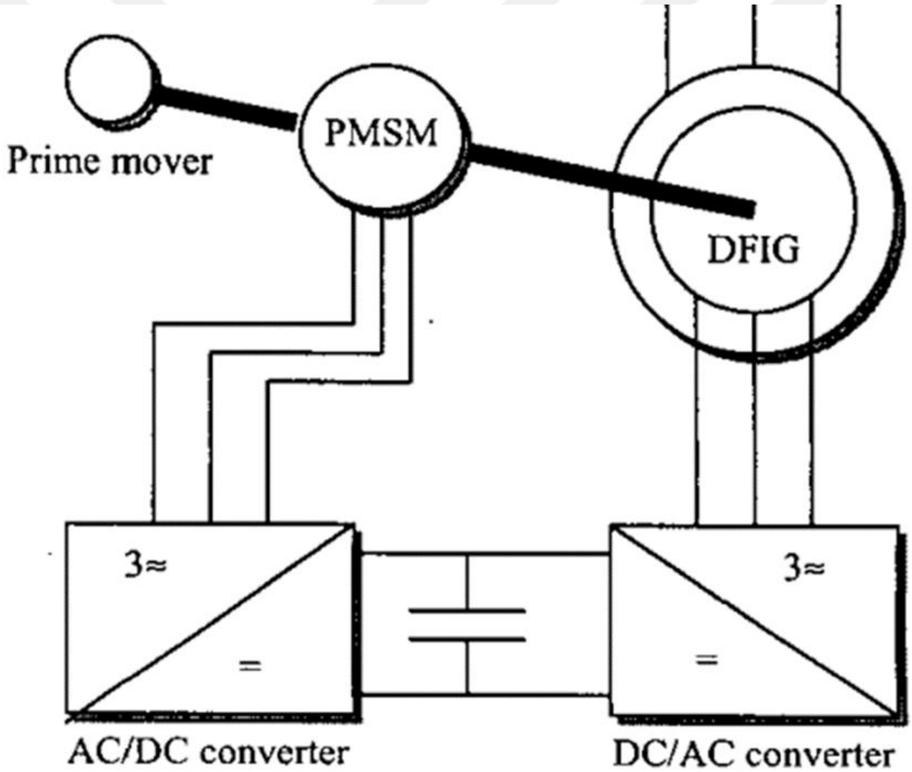

Figure 3.16. The general structure of the DFIG system fed by the PMSG rotor (Khatounian F., 2003).

3.3.3. Other Stand Alone DFIG Application

DFIG, which can be used as an efficient and reliable AC energy source at variable speeds and can be controlled effectively, has become a preferred and suitable system for use in other fields as well as in main aircraft generators. When looked at these applications, it is see that the diesel engine driven synchronous generator applications used in isolated areas are replaced by DFIG based applications. (R. Peña et al, 2002).

Most diesel generator systems use synchronous generators with output voltage controlled by DC rotor current. The main reason for this is to maintain the stator output voltage at a constant value by controlling the rotor magnetic field current determined according to the load demand. Since the machine is already designed synchronously, the frequency is kept constant by keeping the mechanical speed at a constant value, the number of slot-poles, and the angular rotation speed. When looked at this issue carefully, regardless of the amount of load requested, the diesel engine, ie synchronous generator, must be kept at constant mechanical speed. Fuel consumption within the constant speed frame of diesel engine synchronous generators is very high even under very low electrical loads and it is generally recommended by manufacturers to have at least 40% of the maximum generator power active (L. Freris et al., 1990). These two conditions are inefficient, increase fuel consumption, and extremely restrictive parameters. Variable speed operations have many advantages, such as reducing mechanical stress and reducing the fluctuation of power supplied to the system for feeding.

As with DFIG systems, if DFIG is used instead of a synchronous generator in diesel engine driven systems, the speed of the diesel engine increases and decreases according to the requested electrical power and thus the energy required is provided and thus efficiency is increased and fuel consumption is reduced. The next path to follow is the same isolated region as the DFIG power demand is determined by the controller via converter and the PWM technique is applied by the rotor field current is created. In this way, VSCF AC power is obtained with variable speed with high efficiency (M. Rosyadi, 2015).

3.4. Control Methods of DFIG

The ability to produce AC power at constant frequency and voltage at variable input speeds, to respond quickly to changes and disturbances in the system, to quickly and reliably eliminate instability such as mechanical speed changes or sudden load fluctuations is characteristic for DFIG. It is undoubtedly able to present these characteristics thanks to its unique control strategies. The basic principle is the ability to generate AC at constant frequency and voltage regardless of the amount of power needed instantaneously and the instantaneous variable rotational speed. The DFIG control methods are based on generating PWM-based rotor field current through controllers. Also, the control with the power-to-pole analysis technique, vector control by transferring the current-voltage components into the d-q space, or the control methods possible with the stator voltage-control technique from the pole differs in terms of their internal functioning and the stability of the system. Now let's look at each of these control techniques separately.

One of the main reasons why DFIG systems can provide strong and reliable CFCV AC energy under variable speed mechanical revolution is one of the main reasons for the choice of very powerful and reliable control strategies that can respond quickly to changes and maintain stability. In general, the stator terminal parameters, which are controlled by the control and modulation of the circulating field current in the rotor, are realized by differing control mechanisms. In a system capable of withstanding such volatile situations, the time-shift factor can cause serious confusion, and eliminating time-varying components is a desirable option to simplify analysis and control.

3.4.1. Vector Control

The vector control method, which is based on α-β and d-q frame transformations, which are based on Park and Clark transform, has emerged as an effective control method for DFIG applications (AK Gupta et al., 2013). The idea of applying the vector control technique on DFIG was first proposed by Blaschke and Hasse, inspired by the structure and operation of the DA motor drive circuits (M. Loucif et al., 2013.).

It is a classical control method based on the field-voltage orientation based on the vector control (VC) method, which provides the control and stability of the system by decoupling the flux and torque pair, independent subsystems in DFIG applications. After modeling, the characteristic analysis of the system is a method that can be done in a simple way like DC machines and eliminates the cross-coupling elements and makes the analysis simpler (Guo F. et al., 2012).

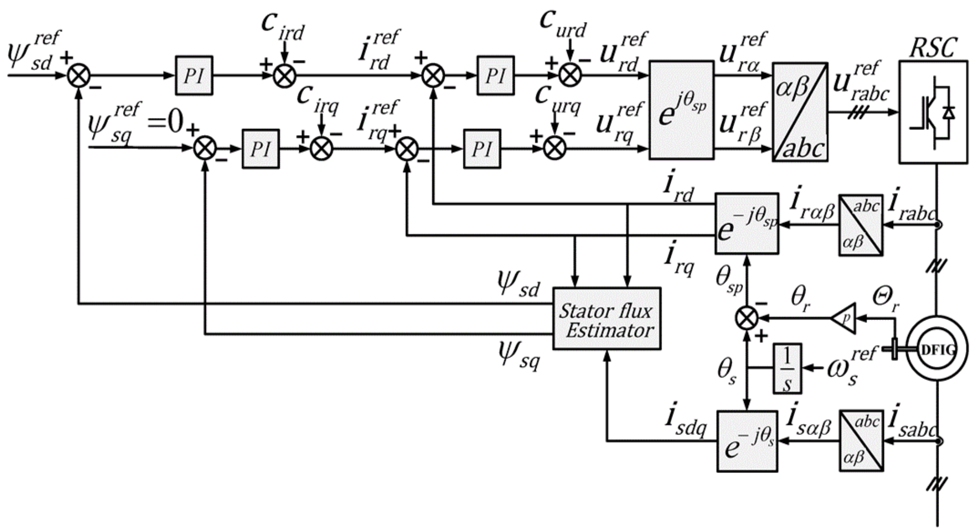

Figure 3.17. Control scheme of the DFIG system with vector control in a stand-alone zone (J. L. Rodriguez et al., 2002).

In this algorithm, the stator 3 phase current values were transferred to the α-β frame and then to the d-q plane before the abc frame and the stator angular velocity

θ_s was converted to the angle value by an integrator. On the other hand, the rotor angular velocity was converted to the rotor angle θ_r with a constant ratio and this value was subtracted from the stator angle and the slip value θ_{sp} was obtained. By using θ_s inverse Euler transformation, stator current q-d values were obtained and the d-q components of stator flux were calculated by a stator flux value block by rotor d-q currents obtained by the same algorithm. As mentioned earlier, when the stator current is on the d-axis, the q component of the stator flux becomes zero, where φ_{sq}^{ref} becomes zero and the difference equation, which is the negative φ_{sq}, passes through a PI controller and summed with the negative of the i_{rq} value. Finally, it passes through a PI controller, where P is calculated as the rotor resistance, and the V_{rq} value is subtracted from this result and transferred to the α-β plane by Euler transformation. This same path is also made for component d of current and voltage and d parameters are calculated. Finally, another module is passed to the 3-phase abc plane by using another module and $V_{r_{abc}}$ values are applied to the RSC and the rotor is fed by the PWM technique.

By explaining the interpretation of the above-seen stand-alone DFIG vector control scheme and the control strategy, it has seen how the vector control method is realized.

3.4.2. Direct Voltage Control

DFIG has become a highly preferred system in isolated areas due to the continuous decrease in battery systems and wind turbine installation fees, the availability of widespread technological advances, and the ability to produce quality AC power at different speeds. On the other hand, fluctuations in the wind, sudden and rapid changes in the load amount connected to the network are the parameters that make obtaining CFCV AC difficult. One of these challenges is the unstable natural regime of wind and fluctuations in energy demand, which may vary daily or hourly. The only way to meet these challenges is to create reliable and fast-acting rotor controller systems and robust controller algorithms. At this point, the direct voltage control DVC technique is an effective and reliable stand-alone DFIG control strategy.

DVC is a method used to control RSC conveniently and conveniently. The basic principle here is to keep the stator terminal voltage and frequency constant about the value of the height of the voltage and the value θ_s which is the angle to the angular position. The value of the rotor current is obtained by calculating the load voltage from the pole using the PI controller. It is can said that Vsd and Vsq values are constant when stator voltage is constant. In light of this information, he can say that stator voltage for the DVC method is calculated by using stator dq voltage values (K. Vijayakumar et al., 2012).

To calculate the reference value of the rotor current, it is necessary to calculate the difference between the currently measured stator voltage and the reference stator voltage, V_{se}=$V_s - V_{ref}$ and process this difference value with a PI controller. The $V_{r_{ref}}$ a value obtained in this way is transmitted to the PWM modulation section to form the appropriate waveform for the rotor, thus keeping the stator terminal voltage and frequency constant (Shukla R. D. et al., 2014).

Direct voltage control is a kind of vector control algorithm based on the DVC technique. Since only the value V_d component of the rotor is calculated and compared with the reference value of the formula $V_s = \sqrt{V_{sd}^2 + V_{sd}^2}$ and the vector control is calculated without including coupling terms with c_{ir} and c_{vr} values unlike VC and the voltage control is directly It was named for controlling and adjusting the rotor voltage (R. Pena et al., 2002).

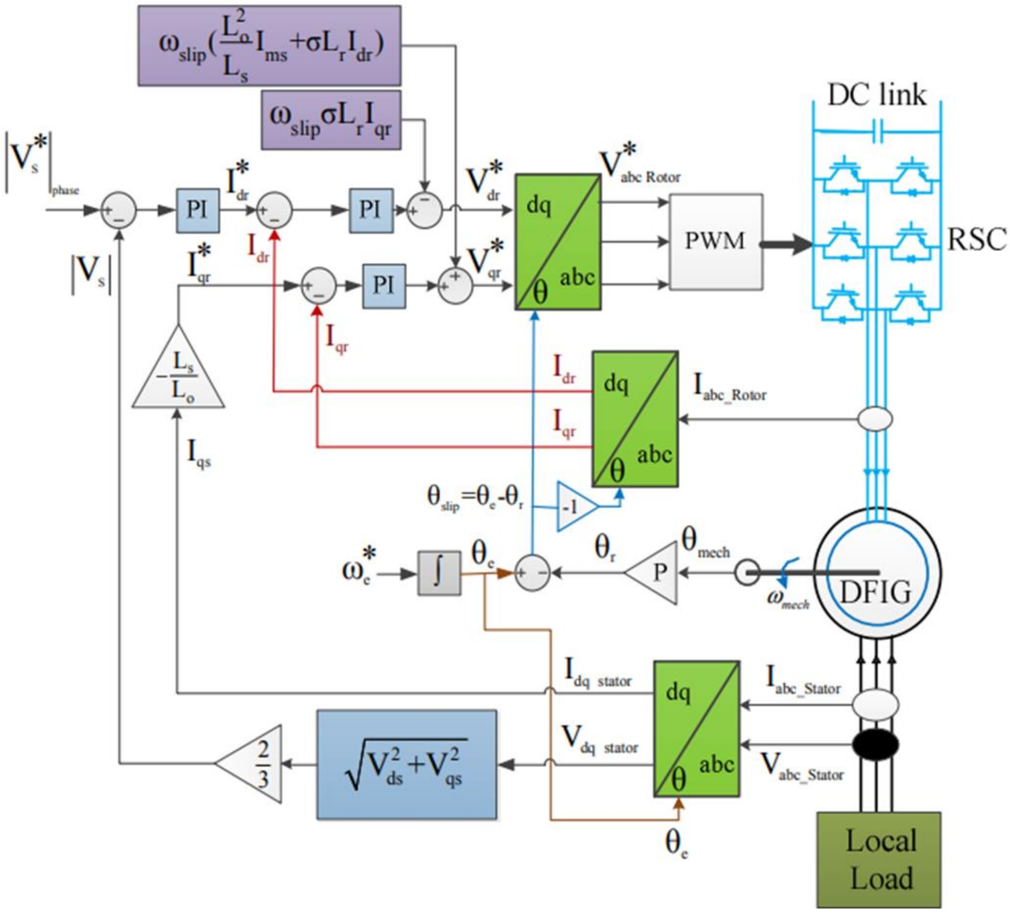

Figure 3.18. Diagram of the control scheme for the DFIG, which maintains a constant stator voltage with the DVC direct voltage technique (Noroozi M. and Farhangi S., 2015).

When looked at this diagram, the first calculated momentary rotor mechanical speed w_r passes through a P controller, and θ_r and stator electrical angle ω_e calculated by θ_e through an integrator I, and the slip angle $V_s = \sqrt{V_{sd}^2 + V_{sd}^2}$ is calculated by taking the difference. Then the stator d-q voltage values were calculated with the formula which is the basic element of the DVC technique. The difference obtained by comparing this value with $V_{s_{phase}}^{ref}$ ref value was obtained by using a PI controller and the I_{dr}^{ref} the value was obtained and compared with the current I_{dr} again it passed a PI controller. This value was calculated by multiplying the slip, leakage rotor inductance and the current q component of the rotor by the voltage obtained and finally V_{qr} was calculated. Similarly, after the V_{dr} value is calculated, dq→abc conversion is performed to obtain the rotor field winding voltage value and feed the RSC using the PWM technique. By using closed-loop direct voltage control DVC, this process ensures that the stator terminal voltage and frequency are kept constant.

3.4.3. Direct Power Control of DFIG

To keep the stator terminal voltage and frequency constant for variable rotor speed, it is the DFIG control strategy that calculates and controls the modulation of the voltage between the reference value and the instantaneous value of the active reactive power, determines the intensity of the stator flux by evaluating the rotor angle and the angular rotation speed, thus enabling control. Sinusoidal PWM (SPWM) waves are generated by the RSC according to the fixed frequency switching technique to generate the desired and appropriate rotor voltage. It is possible to reduce the harmonics that may occur in the system in this way (W. Weiguang and Q. Tian, 2011).

The first step in the application of this technique is to convert and transfer the stator current and voltage values to the α-β reference plane. The total rotor flux on the stator is then calculated using the calculated active and reactive stator power components. These are then calculated using the phase-locked loop (PLL) to determine the stator flux angle θ_s and the rotational speed of θ_s. As the next step, the reference values d-q of the rotor voltage value are calculated for the rotor, which is made with a rotary encoder connected to the shaft. After providing each of these steps, the PWM waveforms generated by RSC are sent to the rotor to keep the output frequency and voltage constant (X. Lie and C. Phillip, 2006).

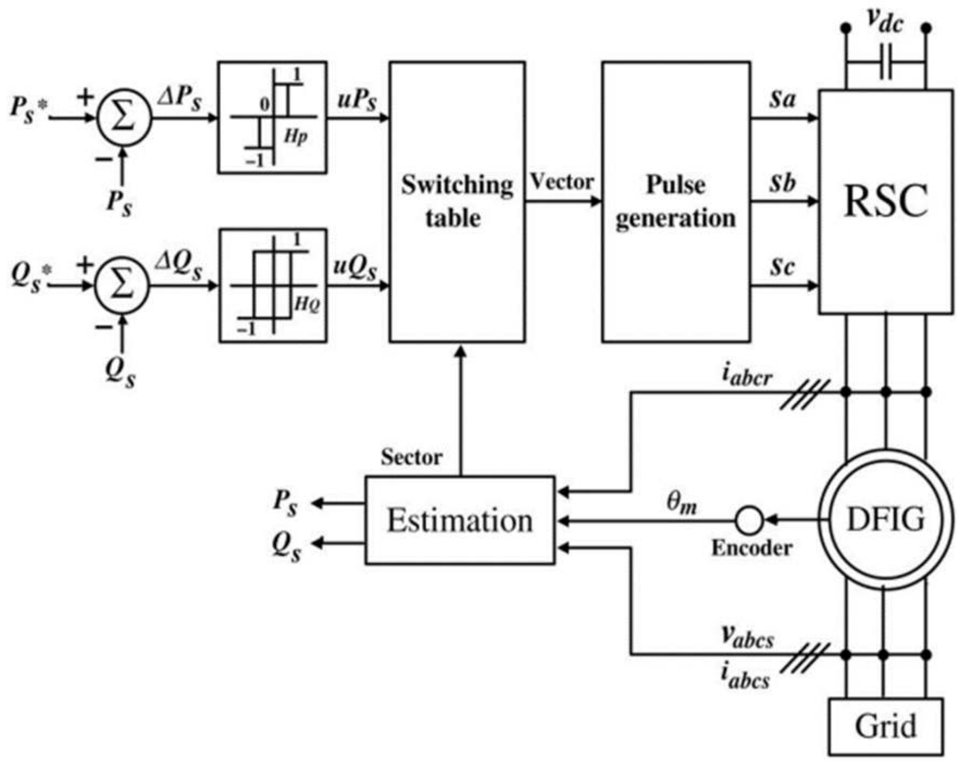

Figure 3.19. Direct Power Control (DPC) The control scheme of a DFIG system with constant stator terminal parameters with the DPC algorithm (M. J. Provost 2002).

When looked at this control diagram, the rotor angular velocity is measured with a speed encoder and the stator three-phase current and voltage values and the rotor three-phase current values are measured. The active and reactive powers of the stator are calculated with a predictor and compared with the reference value entered in the controller's comparison module and the difference is measured. These difference values are selected by a hysteresis controller to determine the optimal voltage value for the active uP_s and reactive uQ_s stator power parameters. In this way, the voltage and frequency at the stator terminal are kept constant according to the instantaneous conditions of the rotor. The difference between vector control and

VC algorithm is that the VC system is current oriented and the DPC system is voltage oriented control systems.

3.5. Summary

At the beginning of this section is started by mentioning the short story of the impact and importance of wind energy on human history and a renewable resource with a natural, renewable and enormous energy potential that has been used for many years. In the following subsections, it is talked about the types of generators and technological innovations used in the methods of obtaining electrical energy from wind power that has been going on for years. With the development of technology and control systems, it has seen that conventional synchronous generators and squirrel cage asynchronous generators (SCAG) have been replaced by double-feed induction generators (DFIG). It is examined how voltage start-up and self-excited procedures are the main problems of DFIG systems for isolated areas. Finally, it has gained extensive knowledge about DFIG by referring to the control methods and methods of stand-alone DFIG systems.

DFIG mechanism, operation, and control, which is considered as a new perspective and technology for aircraft main generators (MG), which is the material that it has identified as the motivation of our thesis study from the beginning, constitute the method part of our study. The sources and information which has studied so far are DFIG applications with 50 Hz 220 V AC parameters for normal world networks. In the next section, it has will worked on DFIG design, modeling, and control algorithm development to obtain AC energy of 115 V and 400 Hz, which is essential for aircraft. And as a result, this model will be tested in the simulation and compared with the results obtained in comparison with the expectations.

4. MODELING OF SYSTEM, CONTROL SCHEME AND SIMULATION

4.1. Modeling of System

In the studies carried out so far the methods of electricity generation available in aircraft have been discussed in detail and researched. Asynchronous type generator modeling which can eliminate the CSD system used to provide synchronous operation of turbine main generators, which is the basic electricity generation unit of aircraft, can be considered as the focus of the study.

DFIG systems, which are widely used in wind turbines, are used as an innovative method in this study. Planes show similarities and overlap with DFIG operated in isolated areas. The basic operating mechanism of the DFIG is based on the interconnection of stator terminals and rotor feed terminals with inverters. Through a stator, the rotor passes the power received by the stator through the modulation block according to the parameters of the control mechanism so that the required magnetic field is formed in the rotor and thus, the stator frequency and voltage are kept constant regardless of the amount of mechanical speed and load that may vary. Implementation of this mechanism in a strong grid-connected system is sustainable and simple, but in isolated areas requires a slightly different and challenging procedure.

One of the difficulties, in this case, is to provide electrical energy to the rotor, which will create the magnetic field required to obtain induced energy from the stator terminal. Since the planes are completely insulated systems, the rotor must be fed in a way that is not connected to any strong grid. In section 3 two preferred methods for isolated region DFIG applications are discussed. The first is the DC link created by a back to back converter placed between the stator and the rotor, and the rotor generates the required magnetic field by feeding with the DC-link energy modulated according to the requested energy. The second is the energy obtained by a PMSG placed on the same shaft as the main machine, by applying the necessary modulation technique to the rotor to obtain the energy in the desired parameters. The method used in this study as an innovative and different perspective than the two mentioned methods is based on the use of batteries that feed the DC power sources already in the aircraft.

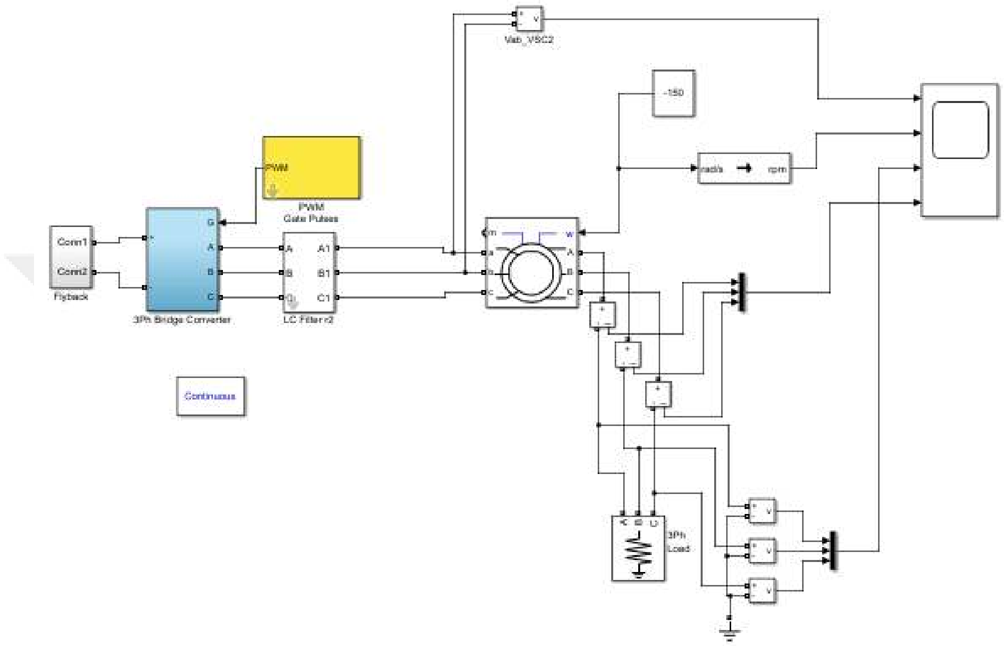

Figure 4.1. The designed entire system.

The required condition for the isolated region to work like DFIG is based on the principle of raising the DC energy stored in the batteries to the desired DC value through a flyback converter. After this step the DC value obtained is applied to the rotor via an inverter modulated according to the control signals and the required magnetic energy is obtained in this way.

4.2. System Configuration

The system designed here consists of the 28V battery available on the aircraft, the flyback converter that creates DC link by increasing the voltage it receives from the battery, the inverter which is modulated DC-link energy for rotor and DFIG driving rotor by modulating the DC-link energy.

Table 4.1. Parameters of asynchronous machine which is used DFIG.

Generator Type	Wound Rotor Asynchronous
Synchronous Speed (RPM)	1500
Number of Poles	2
Mechanical Input (w)	Rad/s
Stator Voltage (V_{rms}, V_L, V_{LL})	115, 160, 200 V
Stator Frequency	400 Hz
Reference Frame	Rotor
Stator resistance and inductance[R(ohm) L(H)	0.5968 and 0.0003495
Mutual inductance Lm (H)	0.0354

28V batteries are available on aircraft and the first step to generate the energy required for the rotor. It is the step that creates a DC link by increasing the energy received from the flyback converter batteries to the desired DC value. It is the part that inverter drives modulating the energy according to the signal coming from the control block to the rotor by using the DC-link energy which is created with flyback converter. And as a final step, it completes the system as an asynchronous machine that outputs constant voltage and frequency from the DFIG stator terminals.

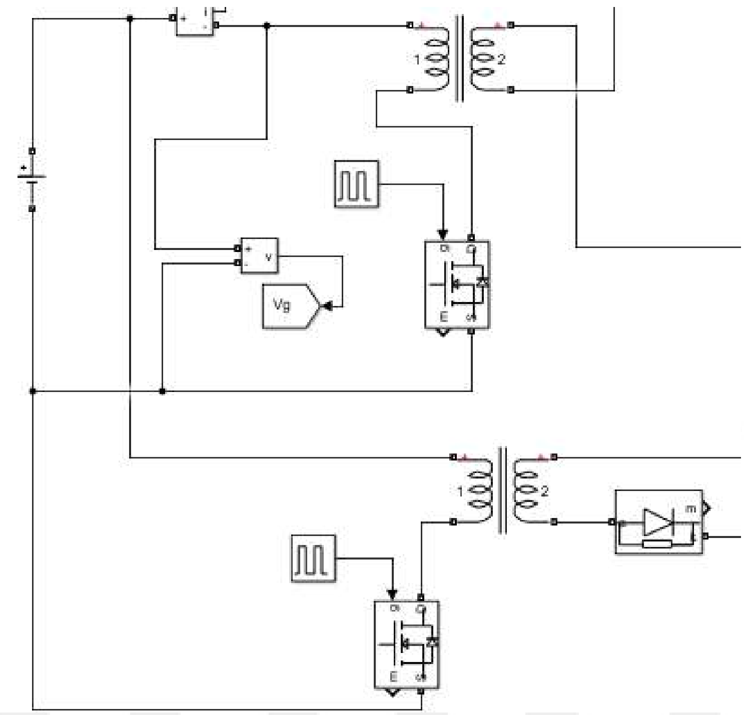

Figure 4.2. ShFigure 4. 2ows the first step of the process, 28V DC source, and two parallel interleaved flyback converters.

This step take 28 V DC from batteries and Generates 240 V DC voltage with two parallel connected flyback converters. In this way, DC-link voltage which is required for inverter supply is obtained.

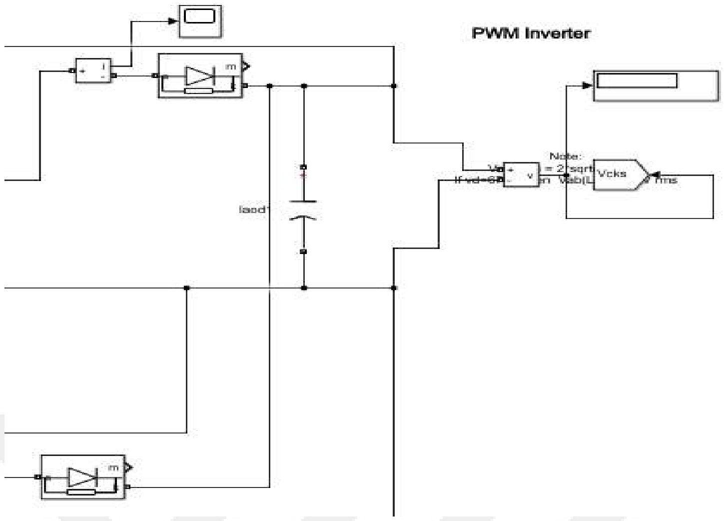

Figure 4.3. The output of interleaved flyback converters and connection of inverter.

The point after this step is the flyback output which is equivalent to the DC-link connection.

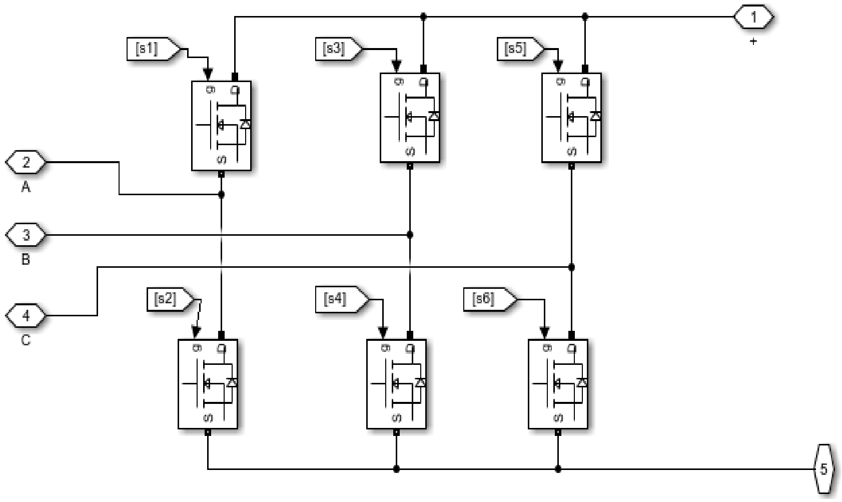

Figure 4.4. Six pulse inverter configuration.

Inverter structure that modulates dc-link output voltage according to incoming control signals.

4.2.1. Flyback Converter Topology

Flyback converters are a sub-branch of switched power supplies (SMPS). SMPS sources started to be used in the 1960s as an alternative to linear power sources. Linear sources constrain the power to go to the source by spending it on an element. Flyback converters operate on the principle of simply storing energy on the Flyback transformer and output capacitor and transferring them to the load respectively. The inlets and outlets are isolated and can have more than one outlet. A basic flyback converter consists of a switching element, a transformer, a diode, and a capacitor. Flyback circuits can be found in various types due to their structure. These types include structures such as a two-switch return circuit, RC reset return circuit.

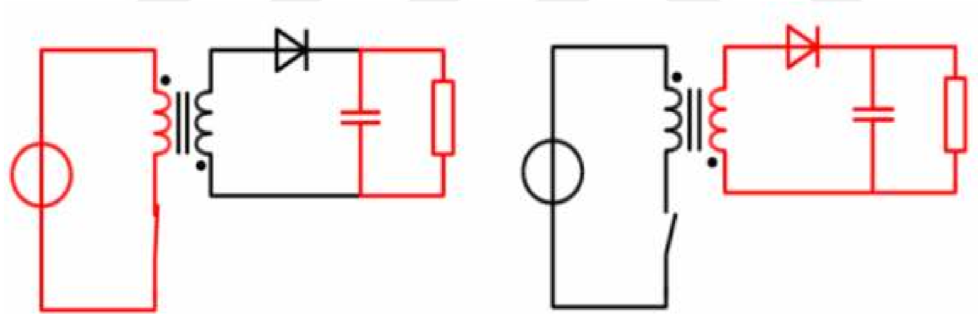

Figure 4.5. Two-position of flyback, the switch is on and of respectively.

In the Figure 4.4 the working principle of the Flyback converter is shown. When the switch is a closed circuit, energy is stored in the primer and core of the Flyback transformer. There is no current output from the secondary winding and the load is fed by the previously charged capacitor. When the switch is open circuit, the magnetic energy stored in the core induces a voltage in the secondary winding and feeds the capacitor and the load passing through the diode. This cycle continues continuously.

If the dot notation in the windings of the transformer is taken into consideration, the windings are wound in opposite directions. In the first case, while the current is entering from the dotted end of the primer, the current should come out from the dotted end of the secondary, but the circuit cannot be completed due to the diode, energy is stored only in the core and the primer and cannot cross.

The output voltage is determined by primary and secondary winding numbers. The control circuit consists of a switching element (generally MOSFET) driven by PWM and by setting the PWM duty cycle value, it is provided to supply the current and voltage appropriate to the load on the output.

Before it is started designing the circuit, it is need to determine some parameters such as input-output voltages, maximum duty cycle value, expected efficiency, switching frequency, control integration, and feedback method.

For this application flyback parameters are $V_{in} = 28V$, V_{out}=240V (DC-link value), P_{out}=200w, operation mode: DCM (Discontinuous Conduction Mode), Duty Cycle=0.45, switching frequency:50kHz, Transformer efficiency: %90.

$$t_{on} = \frac{D_{max}}{f} = \frac{0.45}{50000s^{-1}} = 9\mu s \quad (4.1)$$

$$L_{max} = \frac{V_{in,min}^2 . D_{max}^2 . n}{2.f.P_{out}} = \frac{28^2.0.45^2.0.9}{2.50000.200} = 7.1\mu H \quad (4.2)$$

4.2.2. Three Phase DC-AC Inverter Topology

The inverter basic circuit includes an oscillator, control circuit, drive circuit for power devices, switching devices, and a transformer. The conversion of DC to AC is carried out using switching devices that are continuously opened and closed.

The DC input voltage is turned on and off by power devices such as Mosfets and pulses fed to the primary side of the transformer. The voltage change caused by switching in the primary voltage induces a voltage in the secondary windings.

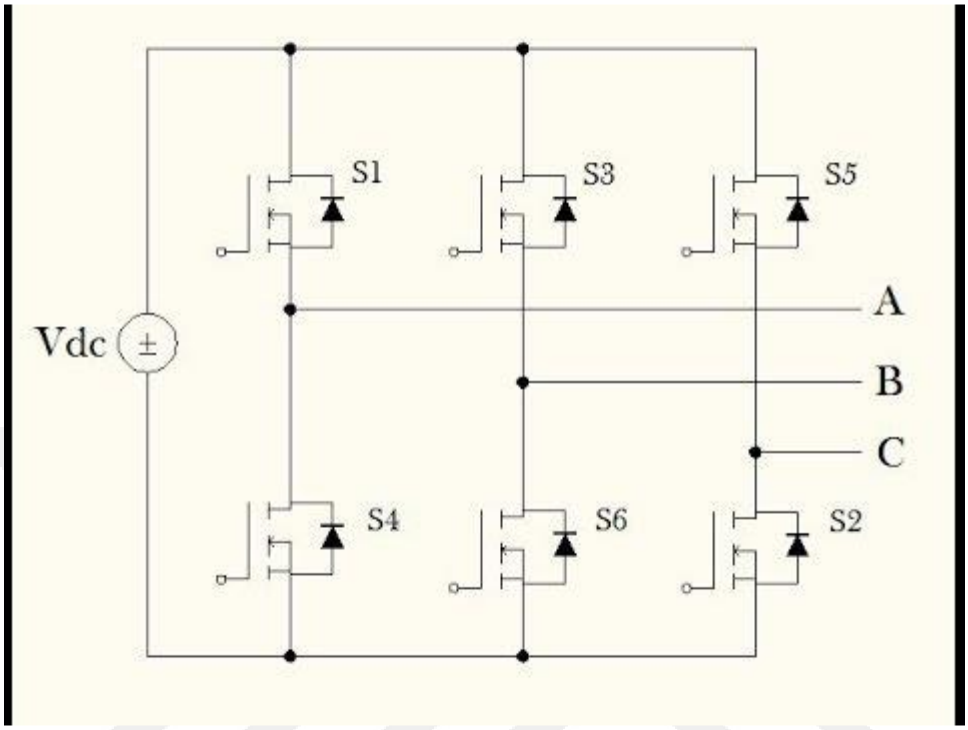

Figure 4.6. The general structure of DC-AC three-phase inverter.

4.3. Control of the System

In this model, the direct voltage control (DVC) technique is applied as in DFIG control which is operated in isolated areas. The method which is essential in the direct voltage technique is based on the fact that the control signals obtained by Park and Clarke transform as a result of the entered reference values keep the stator voltage constant. For this, the phase RMS value of the stator is obtained by taking the squares of the voltage valuesd and q of the stator into the square root. To control this value, the flux q component of the stator is brought to the same axis as the rotor axis and its effect is reduced to zero and the control is provided by the current component of the rotor d.

On the other hand, the angle difference between the mechanical speed and the electrical frequency is calculated as a slip. With the rotor current d component modulated according to the slip value, the electrical frequency is kept constant.

4.4. Obtaining Control Signals

To obtain the necessary control signals, Park and Clarke's transformation and reverse transformation blocks were used. Mathematical equations were learned and transformer blocks available in the Matlab library were used.

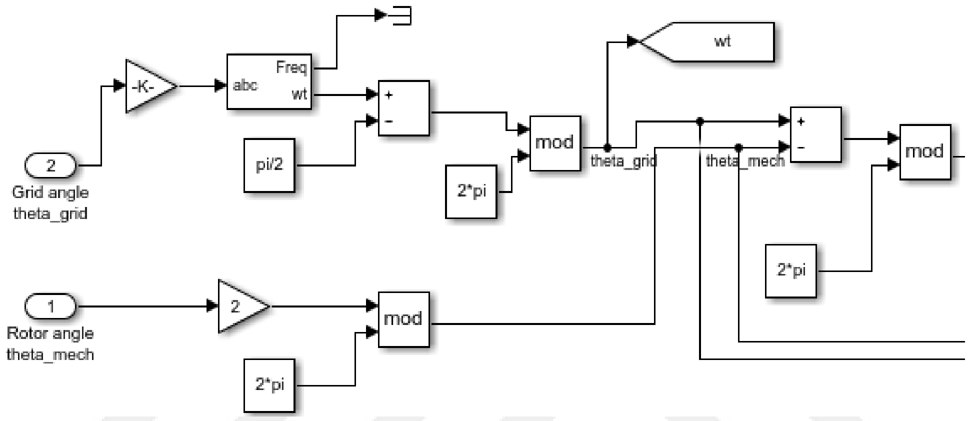

Figure 4.7. Calculation of instantaneous mechanical and electrical angle values for the calculation of slip factor which is the angular slip value.

As a result of the measurement here, The difference between aircraft network angle and rotor mechanical angle is obtained and slip value is calculated.

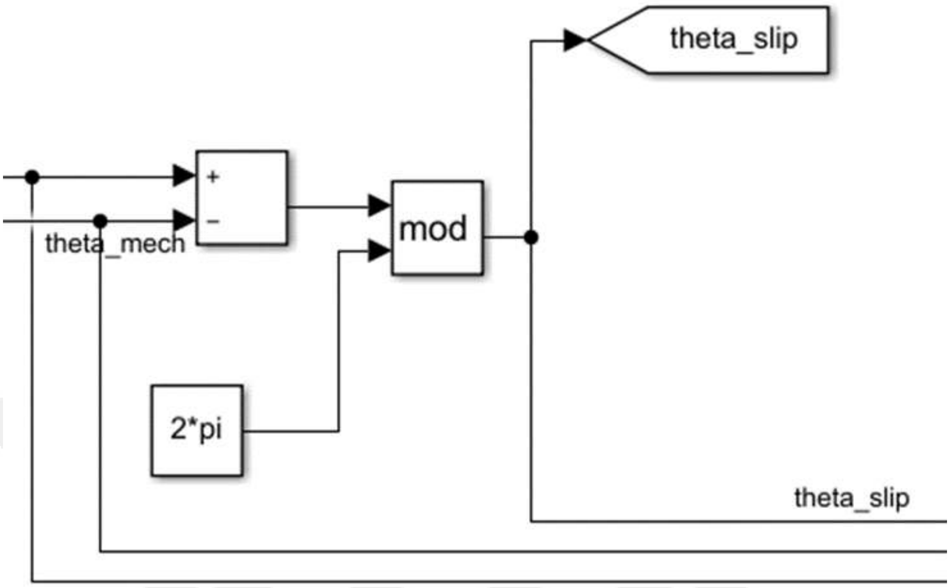

Figure 4.8. Instantaneous values, mechanical and electrical angle values and slip angle with slip angle.

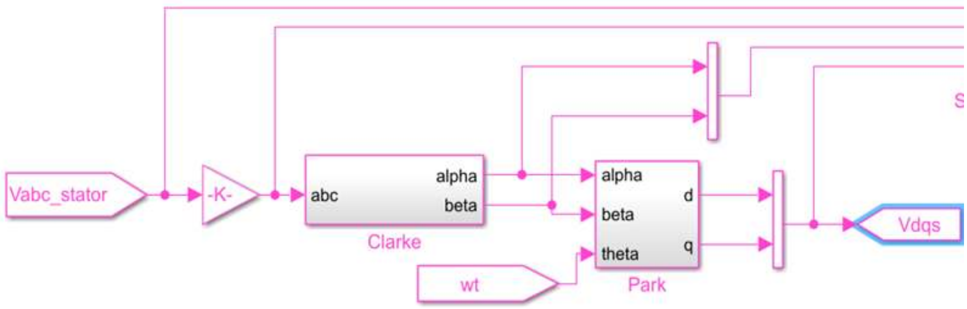

Figure 4.9. Clarke and Park converter blocks used to obtain the voltage valuesd and q used in system control.

Here, alpha and beta are obtained by the Clarke transformation from 3 phase planes. Then, The d and q which are required components for the control signals are obtained by using the park transformation.

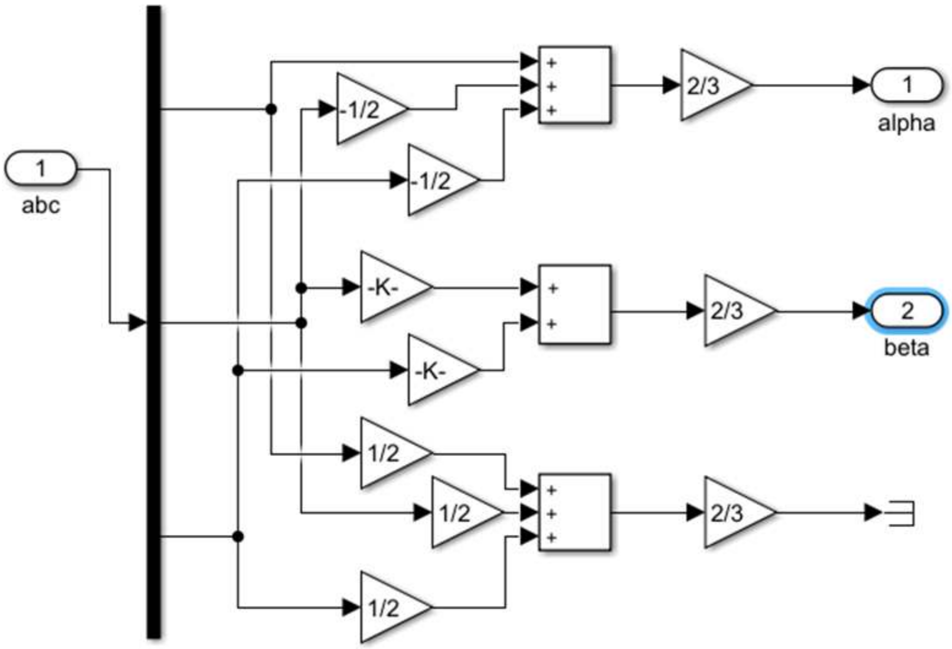

Figure 4.10. Obtaining the α and β components from the Clarke transformation block from three-phase stator voltage.

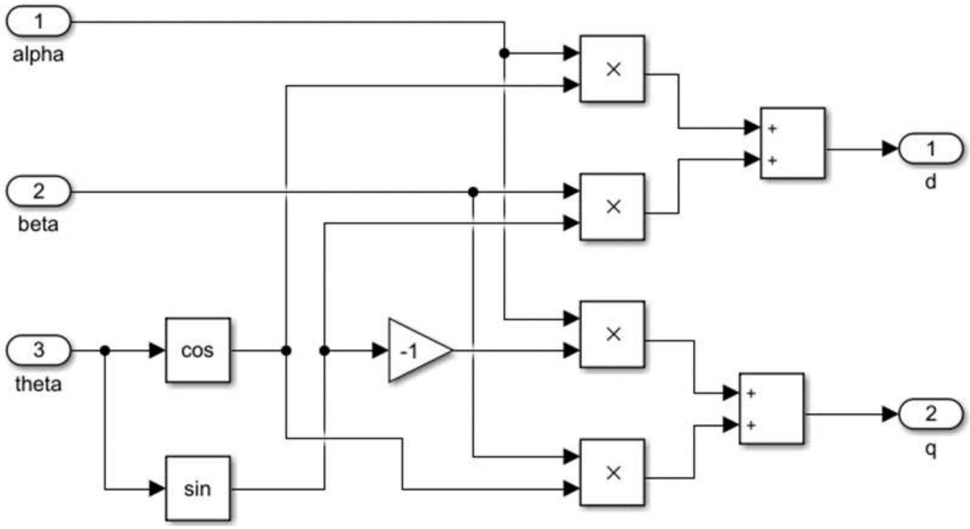

Figure 4.11. To obtain the chips, firstly α and β values obtained with the related blocks, to provide the d and q parameters.

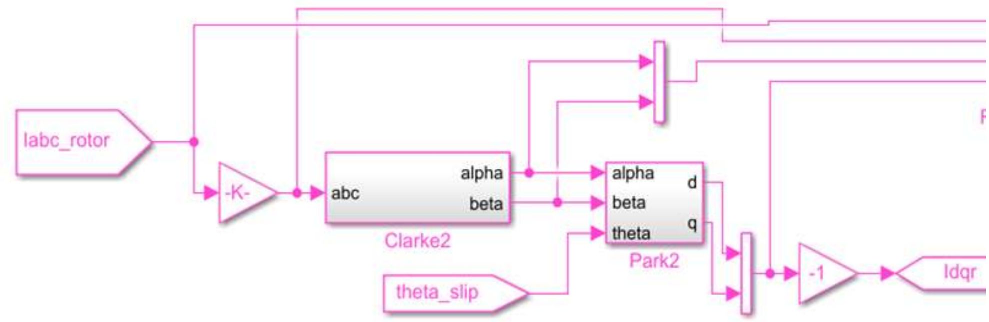

Figure 4.12. Obtaining of rotor d and q components from the rotor three-phase current

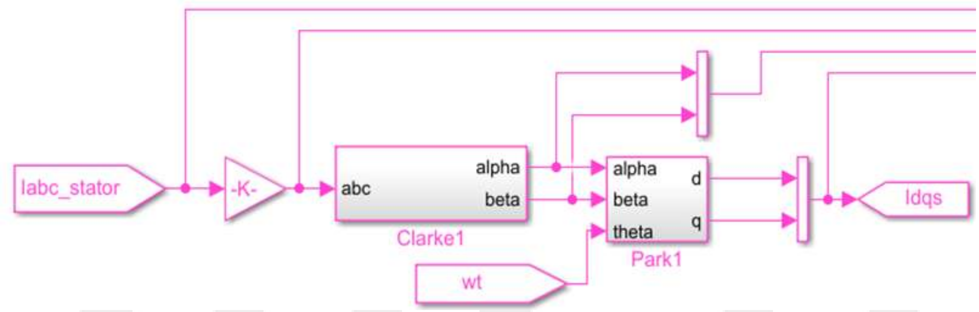

Figure 4.13. Obtaining stator d and q current components

4.5. Adapting the System to a Real Flight

To ensure that this is a realistic study, it is aimed to achieve the VSCF target regardless of the turbine speed which varies according to the instant conditions of a flight to adapt it to a real flight.

As it is known, the main purpose of the jet turbine to which the main generator is connected is to provide momentary flight conditions by providing the thrust to the aircraft. Therefore, the main purpose is to ensure that the generator can operate with fixed parameters regardless of the variable speed that may come at any time.

4.6. Simulation Results and Benchmarking

In this section, simulation results of the same frequency and voltage are provided from the main generator of the aircraft at different mechanical speeds. The synchronous speed of the asynchronous machine used in the modeling was set to 1500 RPM and the input and output values of the aircraft generator for three different options, 900 RPM sub-synchronous, 1500 RPM synchronous and 2100 RPM super-synchronous speeds, were examined and evaluated.

4.6.1. Sub-Synchronous Speed Operation (1050 RPM)

The speed, which is 70% of the synchronous speed, is realized at 1050 RPM which is transferred to the generator after passing through a simple gearbox. This speed corresponds to the situation when the aircraft is running on the ground or when the jet engine is slowing down during gliding.

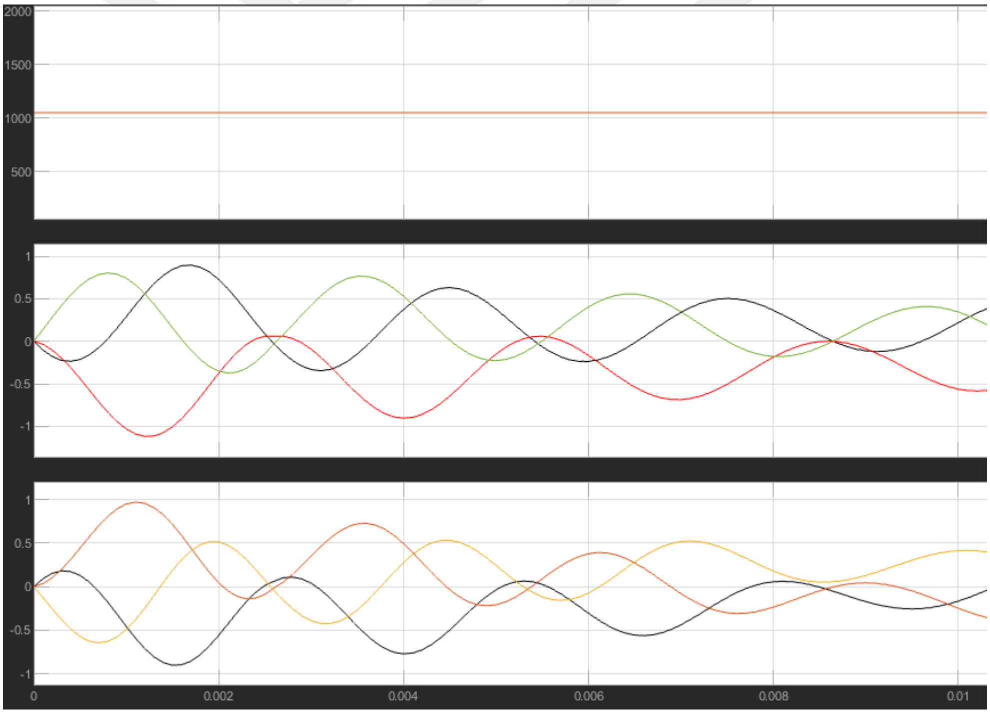

Figure 4.14. Rotor speed RPM, three-phase rotor, and stator current values respectively.

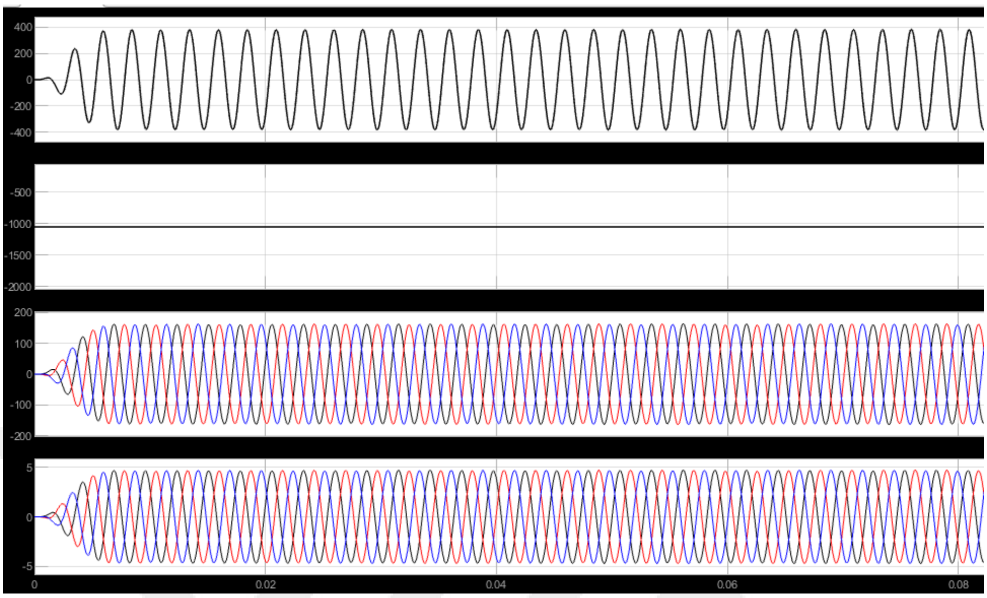

Figure 4.15. Rotor voltage, rotor RPM, three-phase stator voltage, and current values, respectively.

4.6.2. Sub-Synchronous Speed Operation (1250 RPM)

The speed, which is 80% of the synchronous speed, is realized at 1250 RPM which is transferred to the generator after passing through a simple gearbox. This speed corresponds to the situation when the aircraft is running on the ground or when the jet engine is slowing down during gliding.

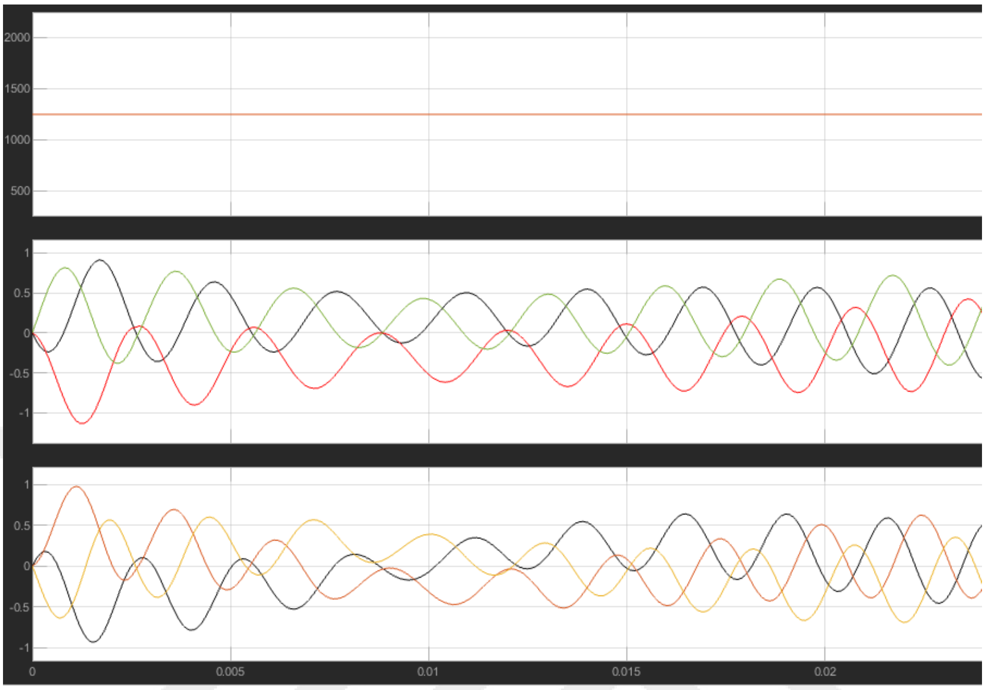

Figure 4.16. Rotor speed RPM, three-phase rotor, and stator current values respectively.

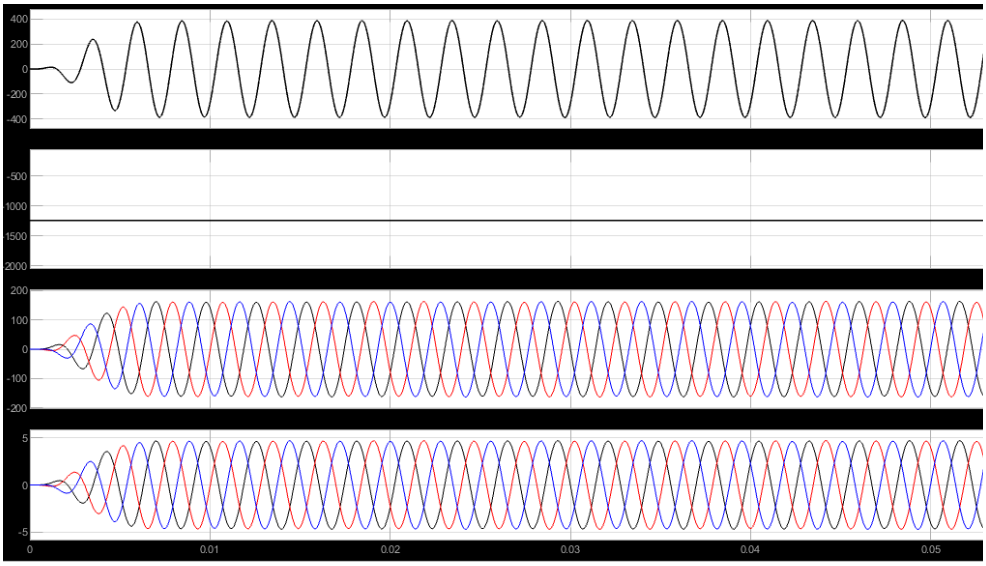

Figure 4.17. Rotor voltage, rotor RPM, three-phase stator voltage, and current values, respectively.

4.6.3. Synchronous Operation (1500 RPM)

This speed range, which is one-to-one or very close to synchronous speed, corresponds to the thrust and speed required for the aircraft to reach its intended altitude and to maintain its height and move forward without much effort.

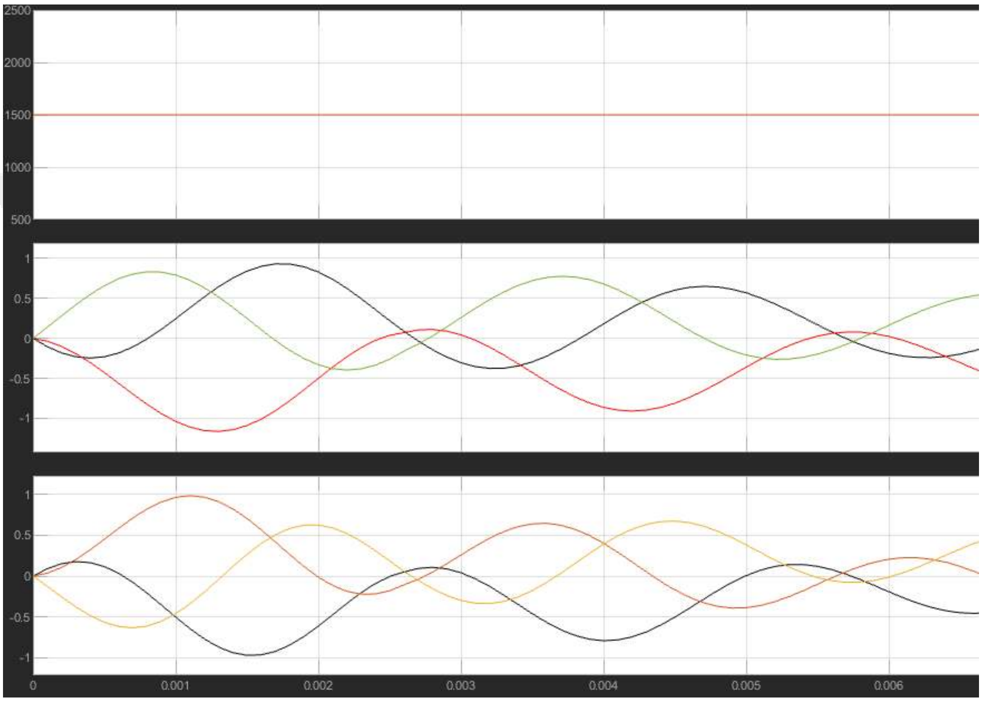

Figure 4.18. Rotor speed RPM, three-phase rotor, and stator current values respectively.

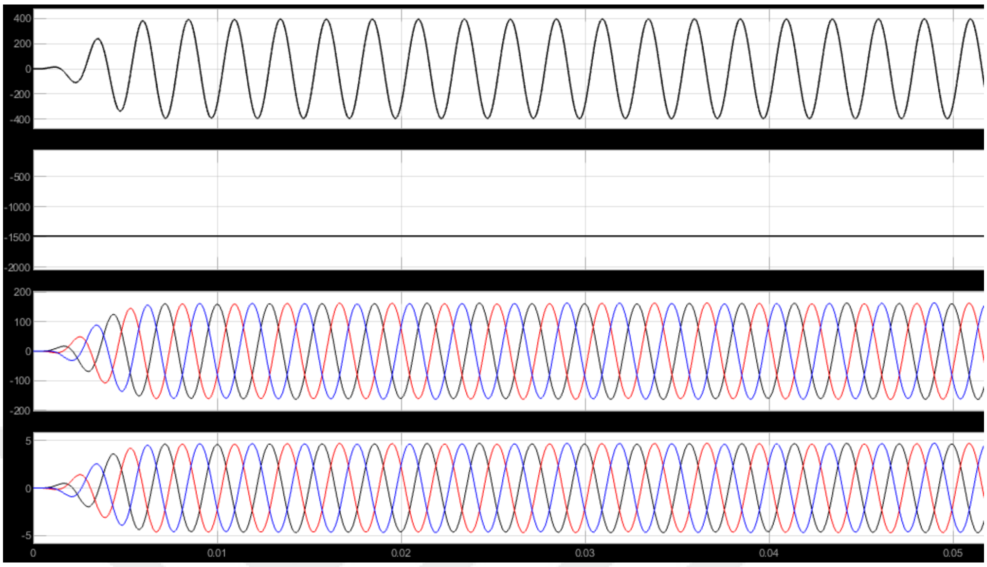

Figure 4.19. Rotor voltage, rotor RPM, three-phase stator voltage, and current values, respectively.

4.6.4. Super-Synchronous Speed (1750 RPM)

The speed, which is 137% of the synchronous speed, is realized at 1750 RPM which is transferred to the generator after passing through a simple gearbox. This speed corresponds to the situation when the aircraft is leaving on the ground or when the jet engine goes uprise during gain speed or positive acceleration.

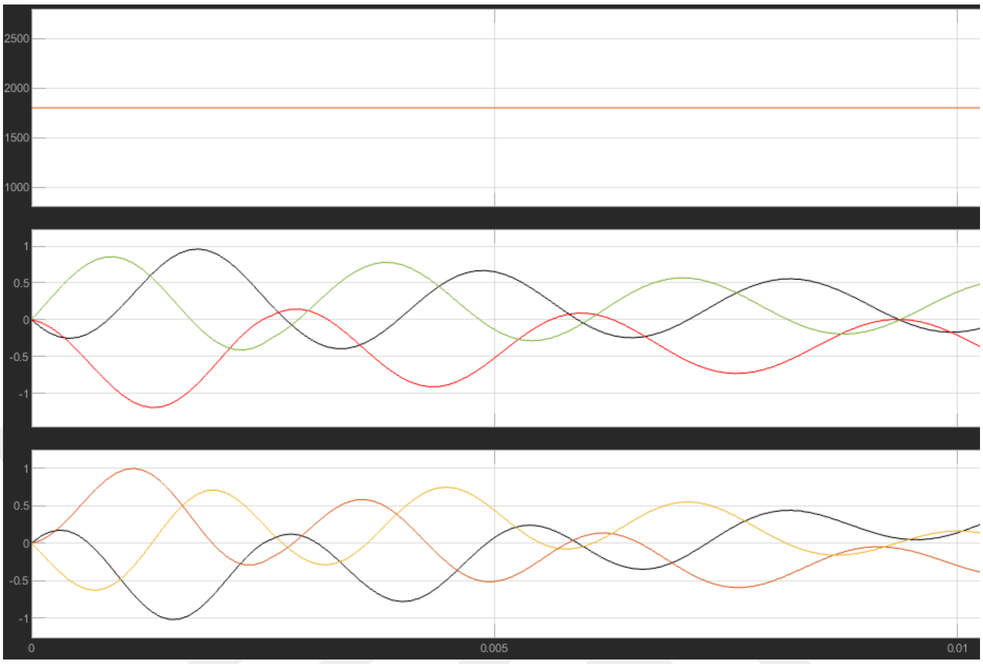

Figure 4.20. Rotor speed RPM, three-phase rotor, and stator current values respectively.

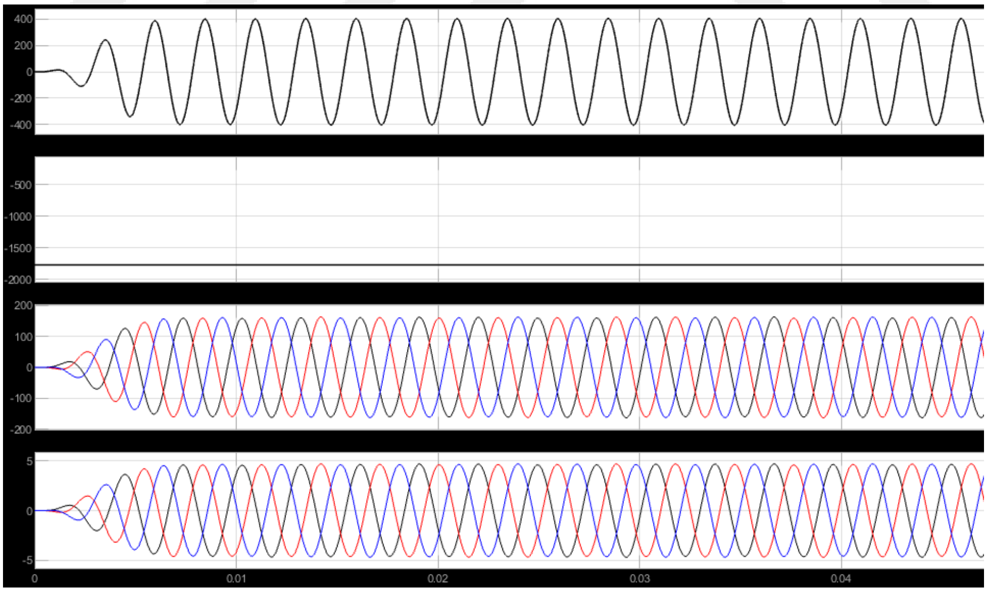

Figure 4.21. Rotor voltage, rotor RPM, three-phase stator voltage, and current values, respectively.

4.6.5. Super-Synchronous Speed (2000 RPM)

The speed, which is 165% of the synchronous speed, is realized at 2000 RPM which is transferred to the generator after passing through a simple gearbox. This speed corresponds to the situation when the aircraft is leaving on the ground or when the jet engine goes uprise during gain speed or positive acceleration.

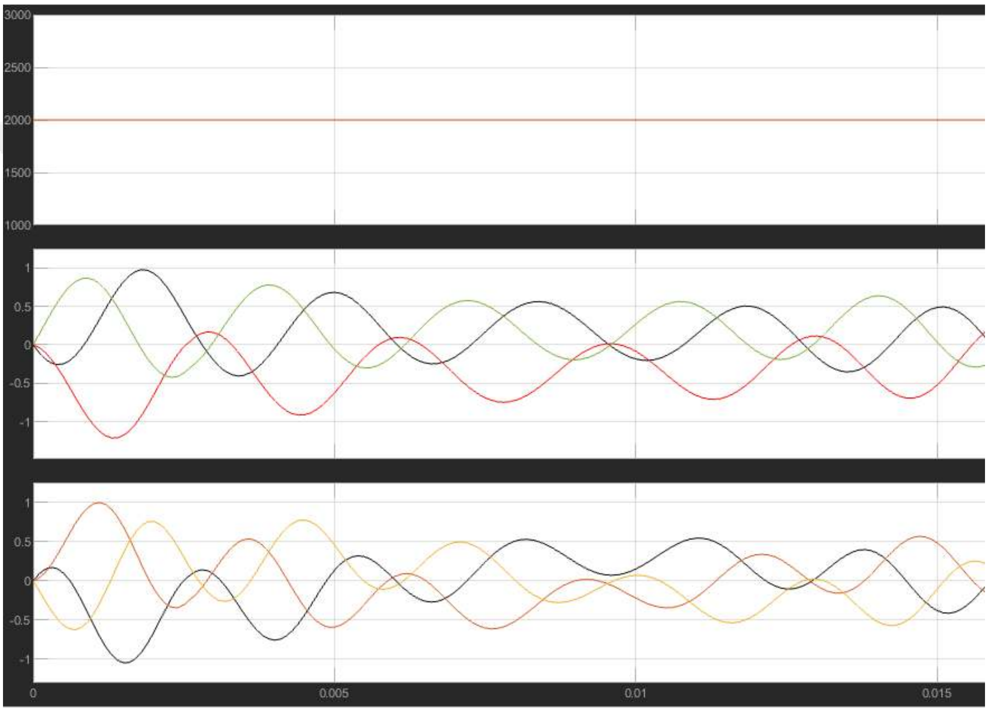

Figure 4.22. Rotor speed RPM, three-phase rotor, and stator current values respectively.

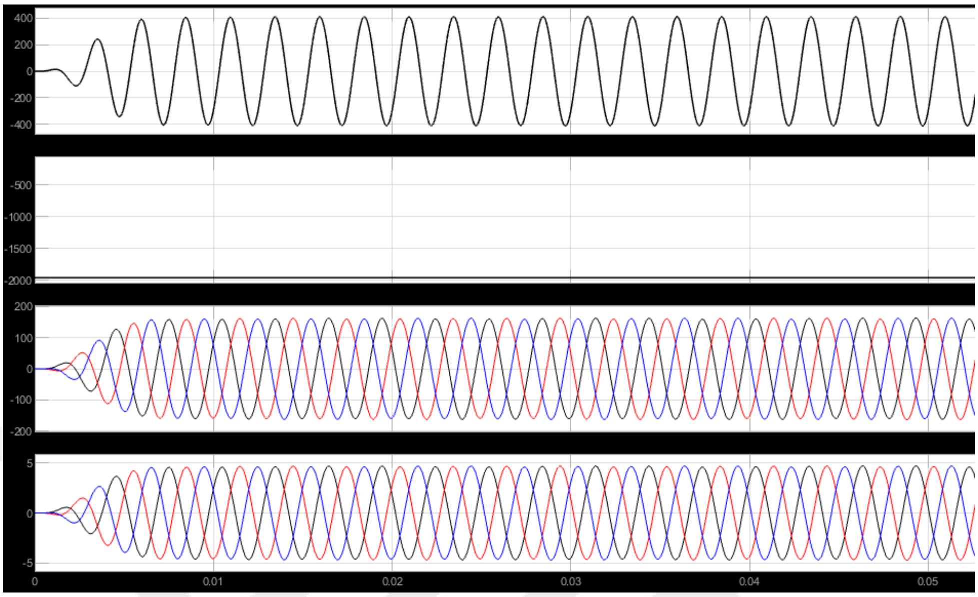

Figure 4.23. Rotor voltage, rotor RPM, three-phase stator voltage, and current values, respectively.

4.6.6. Variable RPM Scenario During Flight

As it is known, planes have turbine speed at different speeds at different moments such as standing on the ground, acceleration, ascension, gliding, and lowering moments. The instantaneous value of this speed can vary instantly depending on the weather and flight charters.

A variable speed scenario has been added to the simulation to show that the output of four different RPM is fixed within a certain period at the time of flight, specific to receiving variable speeds constant output, which is the main subject of this study. In this section, it is shown that the simulation and output voltage and frequency are constant, showing a dynamic speed change at 900, 1500, 2100, finally 1200 RPM values, showing all the parameters of the stator and rotor.

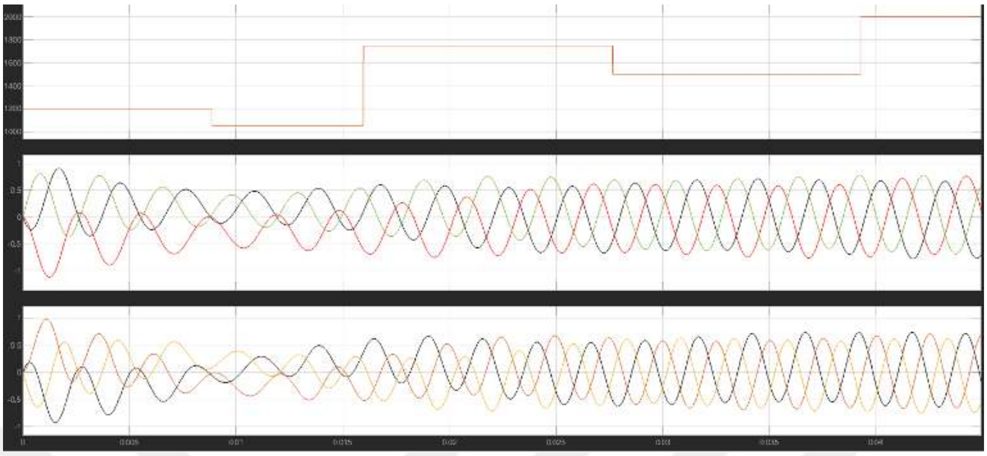

Figure 4.24. Rotor speed RPM, three-phase rotor and stator current values respectively, at variable RPM scenario.

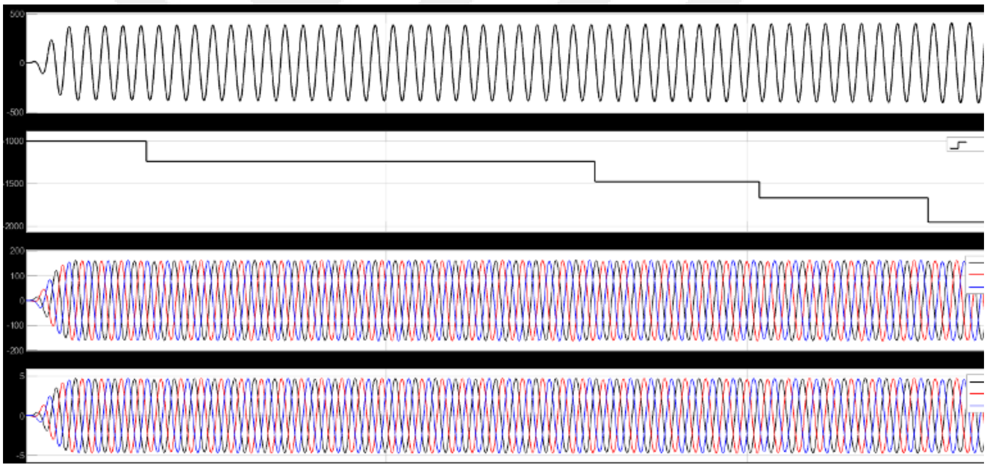

Figure 4.25. Rotor voltage, rotor RPM, three-phase stator voltage, and current values, respectively at variable RPM scenario.

4.6.7. Comparison of Results

When looking at five different speed zones, it is seen that the stator terminal outputs can maintain a constant frequency of 400 Hz with a very small tolerance, and the phase peak value of the stator voltage is 160 V, the phase RMS value is 115 V and the phase-to-phase RMS 200 V can be maintained.

Looking at five different conditions, it is seen that the stator reactive power is compensated by keeping it close to zero as intended so that no additional compensation is required. This is achieved by keeping the current of the stator q concerning d and q with the rotor axis.

On the other hand, it is seen that the rotor reactive power shows a speed-dependent increase. It is possible to say that the rotor active power does not change except for small differences under constant load.

Although the rotor voltage differs in shape and ripple regardless of speed, the oscillation range and form have not changed significantly. And again, because the load is constant, it is can seen that the amplitude of the rotor current does not change, but the modulation changes depending on the speed.

4.7. Summary

The control scheme of the system, the method, and stages of obtaining the control components have been studied in detail and each has been shown separately. In parallel with the turbine speed that may occur under the conditions of the aircraft in a real flight period, it is provided to obtain a fixed output independent of this change.

5. CONCLUSION

In this thesis, an extensive literature reviev was carried out on the production, acquisition methods and storage of the electrical system in aircraft.. In addition, electric production methods used in aircraft, which are not popular, are also discussed. The electrical components that can be used in aircraft are discussed and examined in detail. All the electricity production methods used in aircraft, the advantages and disadvantages are discussed.

The main subject of the study to applicate DFIG to the aircraft. Firstly a detailed literature review on the subject of generator types has been carried out to achieve a reliable and effective system. To analyze and understand the topology of the asynchronous generator, which is the starting point of this study, a review of preferred DC machines, synchronous machines, and asynchronous machines in wind turbines is realized. Most intensively and comprehensively literature review has been made on the structure types and control algorithm of the doubly-feed induction generator which leads the innovative aspect of this study.

Then, with the innovative system desired, studies on modification and modeling of the existing system on the plane were carried out. The simulation results of the designed system under different conditions are examined and interpreted. Turbine rotation speed varies depending on the flight conditions of an airplane. In addition, it can display the amount of energy demanded instantaneously. A separate control algorithm has been designed to tolerate this situation.

In this study, DFIG successfully simulated with Matlalab for generating electricity in aircraft. Stator output parameters are kept constant at variable speeds succesfully.As a future work, the following study is suggested; the viability and effectiveness of the proposed system will be validated by experimental studies.

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