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Emergency Power for Wind Turbine Yaw System

Project initialization tool

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Abstract

The Yaw Power Backup System (YPBS) is a safety system that needs to be incorporated in the Wind Power Plant (WPP) in order to provide emergency power during a power outage. The YPBS enables the Wind Turbine Generator (WTG) to perform a yawing operation in extreme weather conditions. The yawing operation ensures the rotor is aligned with incoming wind, minimizing the acting forces on the blades and structure. The YPBS consists of a central placed emergency backup generator that generates power to the loads. A step-up transformer that transmits power from the generator to the internal electrical system of the WPP network and a shunt reactor that compensates for the capacitance in the collector cable system. The YPBS needs to supply power to the active components and provide frequency and voltage stability in the WPP. The YPBS component design is site-specific and requires information about the electrical infrastructure of the WPP in order to supply the required power and operate safely. In this thesis project, a synthesis tool is developed to identify the loads and to obtain an early estimation of the ratings and costs for an internal evaluation of the YPBS project. A responsibility matrix is also developed to identify the work activities and responsibilities for management of the YPBS project during construction and service phase together with Vestas engineers.

Different models of WPP were developed and investigated for power flow analysis. Two approaches were implemented on each WPP with fixed and variable shunt reactor to validate if the component ratings from the synthesis tool are operating within its capability limits and fulfilling operation requirements. A study for sequential starting of the yaw motors where concluded to validate the required backup generator ratings from the synthesis tool. The results indicate that the synthesis tool is estimating accurate and reliable ratings and is validated by simulations and by existing projects. A YPBS with a variable shunt reactor results in a generator operating more efficiently and can decrease 25 % in size compared to when a fixed shunt reactor is applied. Sequential starting study indicates that if the starting phase is divided in several steps, the generator size can be reduced by a factor of 2.4, as a result of the transient inrush reduction. The study also indicates that a backup generator can be sized after maximum steady state operating condition.

Initialization tool will be applied as an official tool in Vestas and the responsibility matrix is created and agreed on by all involved stakeholders and will be implemented in future projects.

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List of Abbreviations

DG	Diesel Generator
DOL	Direct-On-Line
Genset	Synchronous generator with reciprocating engine
NLTC	No-Load Tap Changer
OLTC	On-load Tap Changer
RAM	Responsibility Assignment Matrix
PBS	Power Backup System
PF	Power factor
SS	Substation
WTG	Wind Turbine Generator
WPP	Wind Power Plant
WBS	Work Breakdown Structure
YPBS	Yaw Power Backup System

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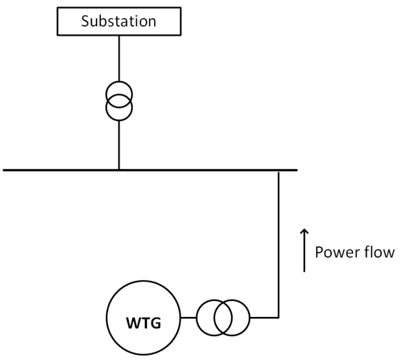
1. Introduction

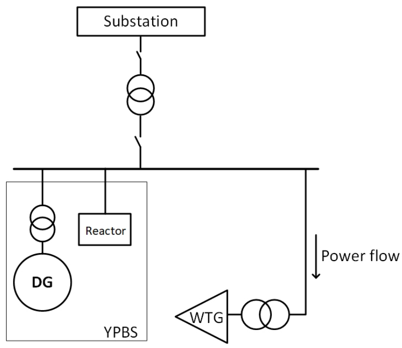
This chapter contains background, purpose, objectives, methodology, limitations and outlines of the YPBS initialization tool project.

1.1 Background

As wind energy starts to compete with conventional energy, it makes up an increasingly larger part of the energy mix and is the fastest growing source of renewable energy. The increasing demand for renewable energy has resulted in wind turbine manufacturers to increase the turbine size and capacity, with Vestas V164 turbine standing almost as tall as the Eiffel Tower. Vestas is the energy industry's global partner on sustainable energy solutions, constantly creating new innovations to develop the technology that will lead the world towards a sustainable future. Larger blades and higher towers result in turbines becoming more sensitive to wind power forces and can obtain great damage during extreme weather conditions. Stresses can be reduced on turbine blades and its structure by yawing and aligning the rotor to track the incoming wind, presuming that constant power supply is available. During these extreme weather conditions power outages could happen suddenly and without power supply, the turbines would obtain great damage resulting in serious consequences for the energy sector and financial losses.



(a) Normal operation



(b) Power backup operation

Figure 1.1: YPBS implemented in the WPP

To prevent these damaging incidents, Vestas has developed a YPBS to protect the turbines in case of a power outage. During normal operation (figure 1.1a) the WTG is generating electric power from wind energy, this power is collected and transmitted to the power transmission system via the substation. During a power outage the internal grid in the WPP is disconnected from the substation and the WTG is not generating power. The YPBS implemented in the WPP (figure 1.1b) will ensure that sufficient power is supplied to components that are active during power backup operation, enabling the WTG to perform yawing operation. The YPBS consists of a generator, step-up transformer and a shunt reactor. The generator supplies power to the internal grid of the WPP via the step-up transformer and the shunt reactor improves voltage regulation and system efficiency by compensating for the capacitive reactive power, generated by the underground power cable system.

1.2 Purpose and task

The purpose of this thesis is to propose the ratings of the YPBS components in order to supply power to the WPP during main power outage. To estimate the size and select the components for the YPBS, so that the cost of this system can be considered in the WPP development phase. To identify the activities and responsibilities during the initiation, realisation and commissioning phase of the YPBS project. In order to carry out the purpose of the work, guidelines for deriving and dimensioning the complementary parts of the backup system are explored. Organisation involvement and cooperation is used to obtain knowledge, collect necessary data and understand the working methods in various departments by being involved from the development to the service phase of the YPBS project. The task of this thesis is to develop solutions for estimating the size of the YPBS components and create guidelines to identify the responsibilities and work activities for the involved stakeholders.

1.3 Objective

The first objective is to gather data and information about the active components in the WPP, that requires power supply during power backup mode. With the required data, develop a initialization synthesis tool based on calculations and simulations for estimating preliminary ratings for the YPBS components. Second objective is to develop a responsibility assignment matrix used during the construction and service phase, to identify the work activities and responsibilities between the stakeholders for YPBS future projects.

1.4 Methodology

The synthesis tool is developed in Microsoft Excel due to its accessibility while analysis and simulation of the YPBS are performed in DlgSilent PowerFactory and Caterpillar SpecSizer. Knowledge is obtained by completing the tutorials and studying the manual for the power analysis software, in order to create a model of the WPP with YPBS and perform simulations. From simulations in PowerFactory, information is gathered to develop and improve the synthesis tool. From SpecSizer, the backup generator size is estimated based on load steps analysis. The synthesis tool will be validated against load flow simulations and SpecSizer analysis. The responsibility matrix is acquired by understanding the responsibilities for the work activities by interviewing and setting workshops with stakeholders within and outside the organisation that are involved in the YPBS project.

1.5 Scope and limitation

The project goal for the tool is to estimate the ratings of the components when initializing a YPBS project, it is not the final rating estimation of the project. The tool will include all the WTG models with support of the YPBS. YPBS is relatively new to the market and data in the existing WPP are confidential due to ownership of turbines belonging to the customer. There have been limitations to access classified data and information. Due to limited support and time constraints a commissioning manual for the YPBS could not be initiated.

1.6 Outline

Chapter 2: This chapter explains the theory for the genset and the YPBS. The main components in the WPP and YPBS are presented.
Chapter 3: This chapter presents the loads and the calculations for estimating the component rating in the synthesis tool. The PowerFactory model of the WPP and simulations with component ratings suggested from synthesis tool are presented. A sequential analysis case in SpecSizer is presented for validation and optimization of the generator size.
Chapter 4: This chapter presents the results from PowerFactory load flow simulations and sequential starting case analysis from SpecSizer.
Chapter 5: This chapter presents the theory for responsibility matrix. The work section activities and the involved stakeholders are presented and the resulting matrix for the YPBS project is illustrated.
Chapter 6: This chapter presents the conclusion of the report and future work discussions.

2. Power Backup System

Power outage can happen suddenly when unforeseen events occur and have serious consequences for the energy sector and communities. Main causes for power outage fall mostly into categories of nature related, equipment failure or by human involvement. Lightning, storms, tree contact, traffic or construction accidents are some events that can cause a power outage. Backup power is essential for safety and protection with applications including hospitals, data centres, water facilities, security and transportation systems. A guaranteed backup power supply ensures that operation is running as usual, saving lives and minimizing economic damage.

A Power Backup System (PBS) is a generating source of power that supplies an electrical system in case of power failure. PBS based on Uninterruptible Power Supplies (UPS) and generator with reciprocating engine (genset) is the most common way to ensure continuity of operation [1]. The requirement for stored energy in a PBS is determined by the tolerated duration of power interruption, the quantity of power supply and the type of load. UPS systems are designed to provide instantaneous power for a shorter power outage to protect critical loads by supplying energy typically stored in batteries. The battery size directly impacts the stored energy capacity and defines the output power and duration capability. The requirements for a longer duration of a power outage will increase the size and weight of the battery and the resulting costs. Therefor UPS systems with batteries are often used during the initial seconds that it takes for the genset to start and become operational [2]. During this short period UPS will protect sensitive equipment and provide possibility for a safe and orderly shutdown. Genset can provide the capability of black starting [1] and supply high power for an unlimited period of time. They can be designed to run as a standby or a continuous power supply unit, with ability to start automatically and run at full capacity within 10 seconds of power failure [2; 3]. YPBS is required to supply high power for longer periods of time to ensure safety in the WPP. For a WPP with 60 WTGs the loads can require up to 10.5 MVA from the power source, during power backup operation. A combination of cost and the demand for high power supply during longer periods of time, results in the selection of a genset for the YPBS.

[1] The capability to recover power from a shutdown condition to an operating condition

2.1 Genset

A genset is part of the electrical power distribution system providing backup power supply in event of power loss. A genset is a combination of an electric generator and a prime mover that converts mechanical energy into electrical energy. The prime mover, also called engine or turbine are mechanical machines that convert fuel energy into mechanical energy. The fuel energy commonly used in prime movers are fossil fuels such as diesel and natural gas. The electric generator is a synchronous generator that consists of two main parts, a stator and a rotor. The stator is the static component and the rotor is the rotating component. A prime mover drives the generator shaft, which is a part of the rotor assembly, directly or via a transmission and turns the rotor. The turning rotor generates a rotating magnetic flux and induces an alternating electromotive force (EMF) into the stator windings due to electromagnetic induction. If the winding is a part of a complete circuit then alternating current will flow and electrical power is generated. A genset can be used as a main source or auxiliary source to generate power for various applications. They can be used for improving efficiency on the power grid and temporarily generate power at peak demands. In nuclear power plants they are used as backup power source and provide safety and reliability for critical components, powering core cooling systems and ensuring a controlled shutdown of the reactor. They are applied in combined heat and power plants to ensure power generation and convert the engine exhaust heat to useful thermal energy for increasing the efficiency of the power plant. A genset has black start standalone capability, meaning the capability to restore the operation of the electric grid independently, in case of a power outage. A genset with a diesel engine and a synchronous generator is the most used technology due to accessibility, power density, running capability and cost [1].

2.1.1 Diesel Generator

A genset consisting of a synchronous generator and a diesel engine is known as Diesel Generator (DG). They are a common source of electrical backup power because of their reliability, durability, size flexibility, fuel efficiency and high torque output [4]. No other internal combustion engine is as widely used as the diesel engine due to its high degree of efficiency, moderate initial investment and operation cost [5]. Fixed installation diesel engines are usually selected for a genset and often operate at a fixed speed. They are optimized with fuel injection specifically for that speed with a governor that regulates the speed by adjusting the injection of the fuel depending on the load [6].

The ISO 8528-1:2018 standard defines rating, performance and application of alternating current gensets that consists of reciprocating internal combustion engines. The standard is intended to help understanding between manufacturer and customer by providing a common basis. The standard defines for instance the maximum power, operation time, average load factor, power factor etc, for all genset types. The general types are Prime Rated Power (PRP), Continuous Operating Power (COP) and Emergency Standby Power (ESP). Genset manufacturers may establish product ratings that exceed the requirements prescribed in the standard, e.g the standard does not specifically set the overload capability requirements however the industry often expects a 10 % overload capability for some of the genset types [7].

The following genset types and requirements are obtained from manufacturer Caterpillar [8]:

- Mission Critical ESP gensets are capable of providing full rating of installed capacity for the duration of an outage. The average load factor for varying load is maximum 85 % of its full capacity rating and can run for a maximum of 500 hours/year.
- PRP gensets are designed to operate at full rating of installed capacity for a period of time but must have an average load factor of maximum 70 % load of its capacity rating. Prime genset has 10 % overloading at peak load demand for emergency use of maximum 1 hour in 12, with a total of 25 hours overload operations per year.
- COP gensets are available to provide non-varying load for an average output of 70-100 % of installed capacity for unlimited time.

Operating a diesel genset below 30 percent of its installed capacity for an extended period impacts the unit negatively and can lead to power losses, poor performance and wear on components. The light load will reduce the heat in the engines cylinder resulting in incomplete combustions and unburned fuel leaks to the exhaust, called exhaust slobber or wet stacking [9]. In case of underloading, additional loads such as load banks should be considered to increase capacity load. If the power load required is higher than a genset can offer, a parallel coupling of multiple genset will offer additional advantage of redundancy and management of underloading conditions. The genset should be sized accordingly to the load and is essential for healthy engine operation and availability [8].

2.1.2 Engine

The diesel engine is an internal combustion engine that converts chemical energy into mechanical energy. The four-stroke diesel engine is typically used in power generation with the process of intake, compression, combustion and exhaust stroke. During the intake stroke, air is injected into the expanded combustion chamber. The compression stroke compresses air increasing its temperature and fuel is injected, the air fuel mixture self-ignites and generates power. Combustion by-products are pushed out from the chamber to the exhaust during the exhaust stroke. The chemical energy used is stored in diesel fuel or biodiesel. Diesel fuel derives from petroleum oil and biodiesel from vegetable oil or animal fats. It is more favourable to use biodiesel in a blend with petroleum diesel for increasing stability and lubrication effects in the engine [6]. During operation, exhaust gas treatment can reduce the amount of pollutants produced by the air fuel combustion. The main pollutants from combustion are sulphur oxides SO_x and nitrogen oxides NO_x. A greater fuel quality without sulphur will reduce the production of SO_x, while more than 90 % of NO_x and particulate emissions can be reduced by implementing modern catalytic converters and particulate filters [6]. These aftertreatment components functionality are impacted by the load, if the engine operates with low loads for an extended period, minimum operating temperature in the exhaust will not be achieved for processing the emission and can cause critical limits of back pressure leading to engine shutdown.

2.1.3 Synchronous Generator

Synchronous Generator (SG) have in general, a uniformly slotted stator laminated core with distributed windings connected in one, two or three phases and a rotor with field poles. The alternating currents in the rotor field windings generate a rotating magnetic field at synchronous speed that induces varying voltages in the stator armature windings. Torque is only produced when the rotor mechanical speed and direction are in synchronous with the rotating stator field. The frequency of the SG is determined by the speed of the varying field and the even number of field poles of the rotor. The rotor speed decreases with a larger number of field poles, a machine at 50 Hz operating at 1500 RPM will require twice as many poles as a unit operating at 3000 RPM. The generator frequency is given by equation 2.1.

$$f = \frac{Ns \cdot p}{120} \tag{2.1}$$

f = frequency in hertz (Hz) , Ns = synchronous speed (RPM), p = number of poles.

An acceptable operation of the SG is achieved when frequency and voltage remain constant or vary in a limited and controlled manner when active and reactive loads vary [4]. The frequency is proportional to the rotating speed of the rotor, a standalone generator controls the frequency by adjusting the speed of the engine by a governor. A governor controls the speed by regulating the amount of intake fuel to the engine cylinders. The engine speed is compared with reference speed, if the two sources differ, a command signal is sent to the fuel control actuator to regulate the amount of fuel entering the engine illustrated in figure 2.1. The generator can absorb

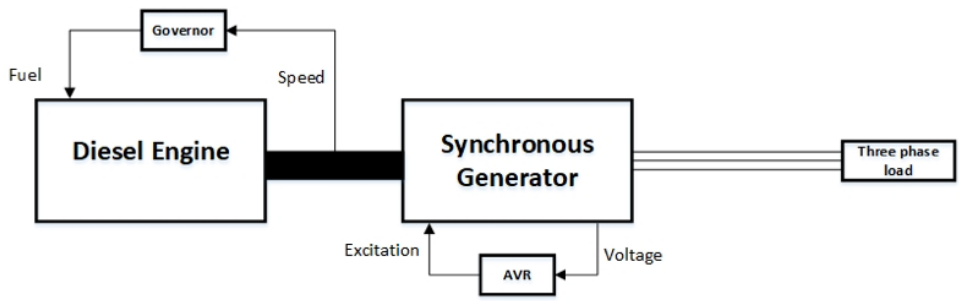


Figure 2.1: Genset with Governor and AVR

or generate reactive power depending on the excitation of the magnetic field and is limited by the SG's defined capability curve illustrated in figure 2.5. Excitation system consisting of automatic voltage regulator (AVR) and an exciter. The exciter is a separate minor generator that provides electrical power to the rotor field and is continually regulated by the AVR to control the generator's output voltage under varying load [10]. The AVR adjusts the voltage to the rotor field winding via the exciter and a greater voltage will increase the exciting current and generate a stronger magnetic field increasing the output voltage of the generator. Many manufactures provide a permanent magnet generator (PMG) exciter as standard equipment for standby generators above 500 kW [11]. PMG excitation provides independent power to the AVR and is not affected by the load application and has greater performance under load variations and better motor starting capabilities than non-PMG [12].

2.2 The Yaw Power Backup System

The YPBS is a genset that generates backup power to the WTG through a step-up transformer into the internal collector grid. It enables the WTG to perform a yawing operation in case of grid outage caused by extreme weather conditions, short circuits or another grid damaging incident. The purpose of the system is to ensure safety of the WTG and its surrounding. Yawing into the wind direction minimizes the loads on the WTG and its linked structure. The YPBS design is site-specific, which means that the WPP's electrical infrastructure needs to be well known in order to determine the ratings of the components. A YPBS ensures that the turbine has enough power to complete a yawing operation, enabling the WTG to track the changing wind direction in wind speeds up to 70 m/s. The WTG type with support for YPBS have an additional wind measurement system and software setting called 'Extended Yaw Mode' to allow the turbine to keep yawing in extreme weather conditions.

2.2.1 Schematic overview

A simplified schematic overview over the WPP with YPBS is presented in figure 2.2. The genset is connected to the MV busbar through a step up-transformer, the reactor is directly connected to the MV busbar. The genset and reactor will only be connected if the grid is disconnected. Which means when the substation transformer is disconnected, either on the MV or High Voltage (HV) side of it. The substation transfers power generated from the WTGs to transmission grid. The DG will mainly supply power to the yaw motors, substation auxiliary and the transformers. During PBS mode only a few components of WPP will be active. The active components are:

- Collector cable network
- WTG transformer, yaw motors
- Substation and generator auxiliary loads
- Substation control system
- Power backup generator, transformer and shunt reactor

SCADA VOB (Vestas Online Business) is a user-friendly interface between the customer's communication equipment and the PPC (Power Plant Controller). The PPC is placed in the substation and is a vital part of the WPP. The PPC measures the active and reactive power generation at the point of connection and use the WTGs to perform control regulation to meet the grid code and power quality requirements. VOB communicates with the WTGs, the DG controller and the substation Remote Terminal Unit (RTU). VOB allows the WTGs to enter YPB mode by activating power backup mode when the grid is out and deactivates the YPB when the grid connection is back. During YPB, the DG controller takes control over the substation and is being allowed by RTU to control the breakers. The DG controller ensures that it is safe for the DG to operate and connect to the system. It also carries out the ramping of the DG during the energization. The reactor will only connect to the grid during YPB mode and is controlled by the DG controller. The DG controller ensures that the correct relay setting is being used for the substation breakers and gets informed by the RTU about the availability of the grid. The WTGs are being connected to the substation in radial feeder configuration, which differs in number depending on the size of the WPP. Feeder is the outgoing internal cable connection from the MV busbar to the connected low voltage WTG load.

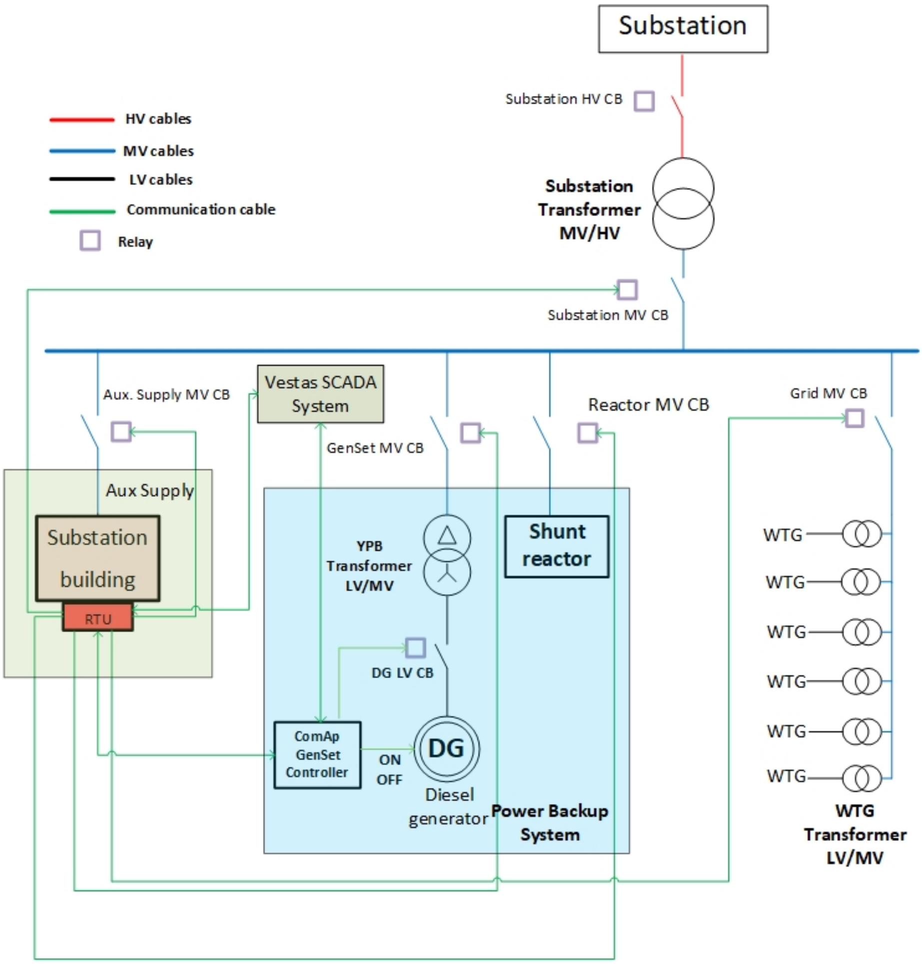


Figure 2.2: Schematic system overview for the YPBS installed in a WPP with six WTGs

2.2.2 Extended Yaw Mode

The power output of a WTG varies with wind speed, cut-in speed is the minimum speed of wind required for the WTG to generate power and is normally at 3-5 m/s. Cut-out at 20-25 m/s is the maximum speed at which the turbine may deliver power. The WTG is programmed to stop its operation when wind speed exceeding cut-out speed, due to safety of the WTG and its surroundings. The Extended Yaw Mode is a control feature for the YPBS, implemented to allow the turbine to yaw under extreme wind conditions with power supply from the grid or from the YPBS. In extreme weather condition with wind speed greater than cut-out speed, the WTG will enter Extended Yaw Mode when a specific speed limit is reached. At this speed the yaw system starts the yawing operation and ensure upwind alignment of the WTG. The WTG will remain in this mode until the wind speed return below cut-out speed.

2.2.3 Yaw system

The three bladed horizontal axis WTG as illustrated in figure 2.3 is the most common type with variable speed, pitch and yaw system as control systems.

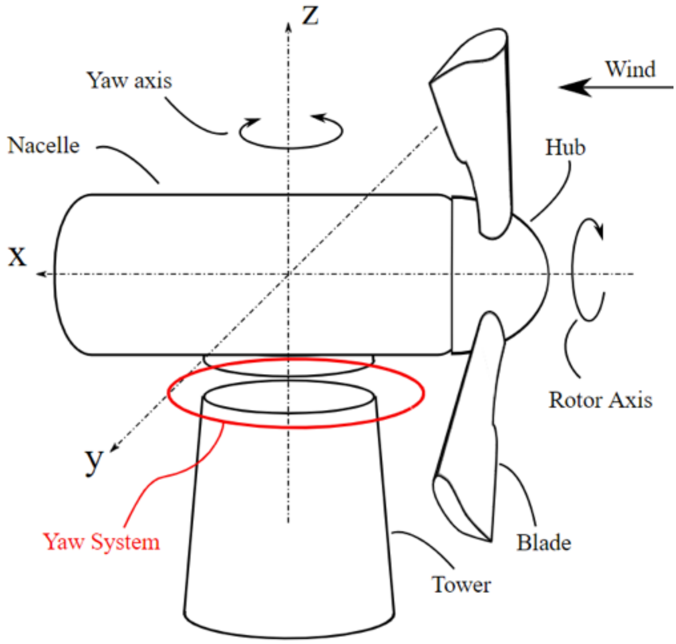


Figure 2.3: Main components of the WTG [13]

The WTG consists of a tower fixed to the ground with a nacelle on top housing an electric power generator. The rotor consists of blades and hub connected to the nacelle via a drive train. The tower and the nacelle are joined by the yaw system. Control and power cables are connected from ground up to the nacelle. The pitch system controls the rotors speed power output by pitching the rotor blades, meaning controlling the angle of attack of the blades about their longitude axis. Pitching is the most effective protection against extreme wind speeds [14].

The yaw system enables the rotor to properly align with the incoming wind to increase the wind energy capture for optimal power input and prevents the WTG from extreme loads during extreme weather conditions. The system is controlled by an automatic yaw control system with a wind measurement system mounted on top of the nacelle and a Global Position System (GPS). The wind system consists of an anemometer for measuring wind speeds and wind vane for detecting the wind direction. The GPS sensors include GPS compass and GPS positioning indicator that determines the rotational displacement of the nacelle and prevents the cables to twist. Twisting angles of the cable are allowed up to 600 degrees rotation with appropriate length and fixings [14]. If the nacelle have turned in the same direction twisting the cables, the yaw system will perform an untwisting operation and turn the nacelle in the opposite direction. The speed of the yaw operation is commonly at 0.5 degrees per second resulting in 12 minutes for a 360 degrees rotation.

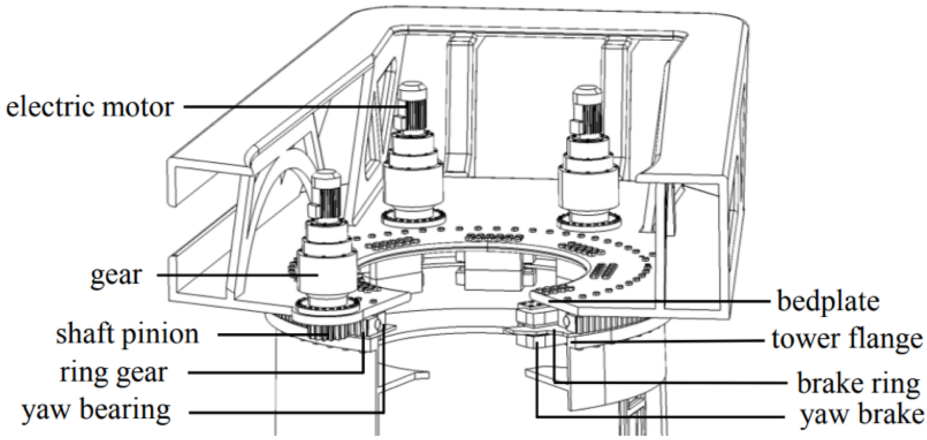


Figure 2.4: Yaw System components [15]

The main components in the yaw system are electrical motors, bearing and brakes as illustrated in figure 2.4. The yaw bearings are used for angular alignment of the nacelle in relation to the tower and are driven by the electrical yaw motors. Yaw rotation is generated by the motor via the planetary gear to the pinion gear and rotating around the ring gear wheel. To prevent wear on the motors arising from the movable parts, the motors operate with a lower output torque until the pinion has engaged to the ring gear and then full torque is applied. The brake system is provided by the generating counter torque of the motor or by mechanical breaks acting on the brake ring.

2.2.4 Yaw motor

The yaw motor is a three-phase asynchronous machine also known as an induction machine that converts electrical energy into mechanical energy. The three phase stator windings are arranged in slots in the stator core such that the phase currents produce a rotating magnetic field. The rotor usually consists of a a uniformly slotted cylindrical steel lamination core with conductors. The rotating magnetic field in the stator will induce voltages in the rotor, if the rotor conductors are a closed circuit then alternating current will flow. The interaction between the produced field and induced currents produces a torque and operates the machine.

The machine is called asynchronous because voltage is only induced in the rotor when there is a difference between synchronous speed of the rotating magnetic field and actual rotor operating speed. This speed difference is called a slip, the machine can only produce torque when the slip exists, and a greater slip gives higher torque within the stable region. When the slip is positive the machine works as a motor with the torque produced in the same direction as the rotor speed. The slip is negative when the rotor speed is greater than synchronous speed. With negative slip the machine will act as a generator with reverse power flow sending power back to the electrical grid and torque is produced opposite to rotor speed resulting in a braking torque.

The starting method of the yaw motor is Direct-On-Line (DOL) and is applied when large starting torque is required, and when the power source can provide a rather constant voltage even with large starting currents [16]. The motor is directly connected to the supply network and starts with full voltage. A DOL starting method represents the simplest and the most economical system to start a asynchronous motor and is the most practised [17]. The motor starting power factor (PF) is up to 0.5 lagging and increases towards unity as the motor accelerates and starting load demand reduces [18]. Motors with a DOL starting method have lower PF compared to other starting methods and are usually within the range of 0.1-0.2 lagging [19].

During the motor starting phase, a large amount of current flows into the stator winding that generates a strong electromagnetic field inducing high voltage and current into the rotor, resulting in a large starting torque. The starting inrush current can be up to six times greater than rated full load current for a short period of time and causes the voltage to drop. If the power is supplied from a robust voltage source e.g. from the main system, the inrush current will cause a small voltage dip. However if power is supplied from a genset the high inrush current can result in a large voltage drop that can inhibit the motor from reaching its operating speed [18]. The voltage drop will reduce the accelerating torque, extending the starting interval and affecting the overall motor-starting performance. The voltage must be within acceptable limits and depends on the motor and load torque characteristics, since the motor must develop enough torque to start from standstill condition. An extreme voltage dip can cause motor control relays or contactors to drop out and disconnect the motor loads from the genset. This will cause the voltage to rise and the process is repeated, causing damage to the contactors and relays. The contactors will in general tolerate a 35% voltage dip although some contactors will start to chatter already at 20 % [18]. When sizing a suitable genset to supply power to the yaw motors, it is critical to verify whether the voltage drop is within the design requirements of the motor [19].

2.2.5 Transformer

Transformers are passive electrical devices that transfers energy across the electrical power system. Power systems consist of generation, distribution and interconnection points. Transformers are used when transition between voltage levels is required. Step-up transformers increase the voltage coming from the power generator and step-down transformers reduces the voltage and are used to supply the distribution network. The main types of transformers are power transformers with single phase, or three phases typically rated at 500 kVA or above [20].

The transformer operational principle is to use a magnetic field from one conductor and induce a voltage into the second conductor. When alternating current flows in the first conductor a changing magnetic field is generated and produces flux via the core. The varying magnetic flux link the second conductor and voltage is induced. The induced voltage is proportional to the coil turns and the rate of change of magnetic flux through the coil.

Transformers have very low losses and are highly efficient, the efficiency level is at 99.5 % or greater for the power transformers. The losses are core losses (no-load losses) and load losses, the core losses are the required power to keep the core energized and are primarily based on voltage and frequency. The load losses derive from load current flowing through the transformer in the primary and secondary windings. Energizing the transformer requires huge inrush current to magnetize the core, the magnitude of the inrush current can be 3.5 - 40 times the rated full load current [20]. The excitation characteristics are expressed by the non-linear flux and magnetizing current relationship. In steady state the transformer is designed to operate below the knee point of saturation curve. Beyond this point the core becomes saturated and additional current will not increase the flux. During energization the flux is increased above the saturation levels increasing magnetizing current drastically. The magnitude of inrush current depends on the supplying source, remanence [2], core magnetizing characteristics and primary winding resistance. When a transformer is taken off-line, remanance remains in the core material and can be 50-90 % of maximum operating flux [20]. When voltage is reapplied to the transformer the inrush current rebuilds the flux with the existing remanence. Once the flux in

[2] Residual flux in the magnetized material

the core reaches saturation levels the winding inductance is reduced and only the impedance of the power supply and the winding resistance are limiting the inrush current.

When the supply source is a genset the inrush current is limited by the high impedance of the synchronous generator. This causes the magnitude of the inrush current to be lower compared to when the main system supply is powering the transformer. When the genset and transformer have the same ratings, the inrush current is generally in line with the transformers full load current and typically require 5 % of genset rated power to magnetize the transformer under no-load condition [21].

2.2.6 Power cables

The metals used as conductors for power cables are predominate copper and aluminum due to their low resistance characteristics. Each of these metals has advantages that might outweigh the other depending on the conditions. Copper conductor has lower resistance that requires smaller section area by a factor of 1.6 compared to aluminium for the same ampacity[3]. However, aluminium is substantially lighter than copper enabling longer lengths to be safely handled and is lower in cost, making it more economical per amps and is generally more used for MV distribution networks [22]. The conductors are rated by their cross-sectional area, for medium voltage the range is from 35 to 1000 mm^2 with a larger conductor having the greater ampacity. A conductor is a distributed capacitor that stores electrical energy in the form of an electrical field, the amount of charge that can be stored is called capacitance and is measured in Farads (F). The conductors are a source of reactive power and have high capacitance and generate reactive power under all operating conditions [10].

2.2.7 Shunt reactor

Shunt reactors are the most compact and cost-efficient device to compensate for the capacitive reactive power in cable systems to improve voltage regulation and system efficiency [23]. The construction of shunt reactors is of dry-type or liquid immersed type and can be designed for indoor or outdoor, with single phase or three-phase. Shunt reactors have two configurations, with a core or without (air-core). The air-core type has insulating structure instead of a core utilizing the magnetic circuit that surrounds the coil to contain the flux. The core type has the similar magnetic circuit construction as the transformer except with the intentional air gap where the magnetic energy is primarily stored. Oil or insulating liquid is used for the liquid immersed type as a cooling medium that circulates within the windings and dry-type reactors are generally cooled by air circulation. The reactor can be directly connected to the power line or adjacent bus. It can also be connected to the power line via tertiary winding of a power transformer. The connection can be permanent or switched in via a circuit breaker depending on the load. Directly connected shunt reactors are usually of liquid immersed type. Tertiary connected shunt reactor is of dry-type or liquid immersed type and the connection depends on the capacity of the tertiary of the transformer. In most instances there is enough unused capacity for the connecting shunt reactor to deliver full compensation [20].

[3] Current carrying capacity

The cable system generates leading reactive power when lightly loaded and absorbs inductive reactive power when heavily loaded. The changes are usually made step wise and are followed by a reactive power compensation. Traditional shunt reactors have fixed ratings and are switched in or out depending on the load variations, resulting to step changes in voltage level and more stress to the breakers. For a dynamic compensation during varying load conditions a shunt reactor with variable inductance is used. A variable shunt reactor connects and disconnects the windings within the unit by a tap changer and regulates the amount of inductive reactive power generated. There are primary two types of tap changers, No-Load Tap Changer (NLTC) and On-Load Tap Changer (OLTC). NLTC are applied when the reactor rating does not require frequent changing and the adjustment occurs while the reactor is off-load and is de-energized. OLTC can adjust the rating of the reactor during operation and are used in applications where dynamic compensation for varying load conditions is required.

2.2.8 DG operating capability

The DG is rated in terms of the maximum power output in apparent power S (volt-ampere, VA) at a specified voltage with PF usually at 0.80 lagging. PF is the ratio of active power to apparent power where apparent power consists of active and reactive power. Active power P (Watt) does useful work and is the real power transmitted to loads. Reactive power Q (volt-ampere-reactive VAr) is related to the energy stored in inductive and capacitive storage components. Reactive power is needed in electrical machines to create magnetic fields and voltage induction, enabling these machines to operate.

Inductors store energy when the absolute value of current rises and delivers it back whenever it reduces. Capacitors store energy when the absolute value of voltage rises and delivers it back whenever it reduces. When the current and voltage are in phase the ratio of active power and apparent power is one and power factor is unity. Lagging PF, when inductive or overexcited, is defined when current lags the voltage with a positive power angle. Leading PF, when capacitive or underexcited, is defined when the current leads the voltage with a negative power angle. By convention a DG operating with lagging PF is producing reactive power and when operating with a leading power factor is absorbing reactive power. Every DG has its own capability curve defining the operating characteristics and safety limits for generation of active and reactive power. P-Q (active - reactive power) capability chart for a standby genset is represented in figure 2.5, stability limits illustrated with red coloured line. Operating points must be inside the area determined by: 1 - minimal rotor field winding current, 2 - maximal engine power, 3 - maximal armature stator current limit, 4 - maximal excitation current (end heating limit). The active power output is limited by the engine capability and the reactive power output is limited by the armature current limit, field current limit and end region heating limit [24].

The power ratings of the DG are presented in per-unit quantities, representing the ratio of actual value and the base value of a unit. The vertical axis represents the magnitude of active power and horizontal axis the magnitude of reactive power. During load condition when line inductance dominates capacitance, the DG will operate in the first quadrant generating reactive power. During no-load condition

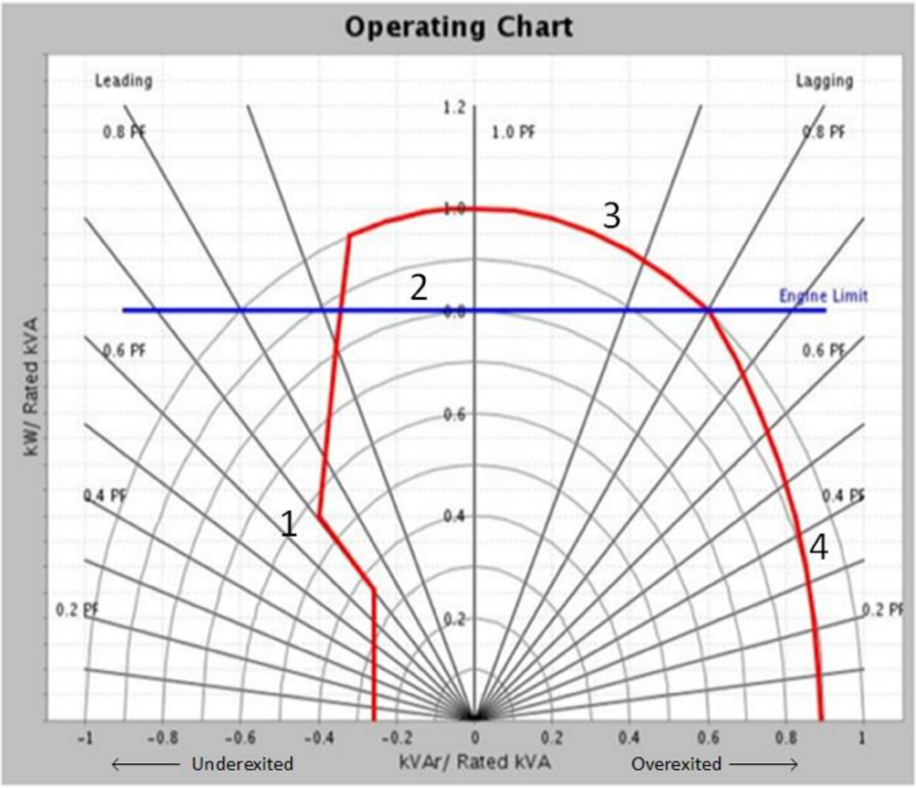


Figure 2.5: P-Q operating chart for the DG (Caterpillar)

when line capacitance dominates the inductance, the DG will operate in the second quadrant absorbing reactive power. When sizing the DG it is crucial for all operating points to be within the limit boundary for the machine to operate safely. For an efficient operation of a power system, the reactive power flow needs to be minimized and mainly transfer active power. Compensating devices are added to absorb or generate reactive power to control the balance of reactive power and control of the voltage. Devices used for this purpose include shunt reactors, shunt capacitors and tap changing transformers.

A DG should operate within the reactive power limit between -0.25 and 0.9 per-unit, this can be achieved by proper sizing the shunt reactor. An undersized shunt reactor does not compensate for the total capacitive load of the power cables and the DG will need to absorb reactive power. If the shunt reactor is oversized, the DG will supply reactive power to compensate for the inductive load.

3. YPBS synthesis tool

The YPBS synthesis tool is a calculation tool based on Excel sheets to estimate the required ratings for the DG, YPB transformer and shunt reactor for the specific WPP. The tool will be used to identify the ratings and costs for early evaluation of the YPBS project. The WPP component data considering WTGs, yaw motors, transformers, MV internal cables system, substation auxiliary and generator auxiliary loads, are required for the synthesis tool to estimate the ratings of the YPBS components. The tool will include all WTG models that have YPBS support.

Input data:

- Number of WTGs and model
- Voltage and frequency on MV busbar
- Transformer ratings
- Cable length and dimension
- Selection to include auxiliary loads

Output data:

- Generator ratings
- Reactor ratings

The Structure of the YPBS synthesis tool is one main sheet represented in figure 3.1, with input parameters, background calculations and results. The data required for calculations are in hidden sheets, WTG data, cable data and the auxiliary data. The Main sheet requires the model and number of WTGs as input and will retrieve data from WTG sheet and Auxiliary load sheet to calculate the estimated consumption for the WPP during power backup supply. For the MV internal cable system the input fields consist of line to line voltage, grid frequency, cable length and dimension. Output data for the capacitance of the cable type will be retrieved from the cable data sheet and the total reactive power generated from the cables is calculated. The shunt reactor ratings are calculated to compensate for the capacitive reactive power generated from the MV underground cables.

The tool will consider a shunt reactor with NLTC or OLTC and suggest generator rating that operates within the operating chart limits for both cases.

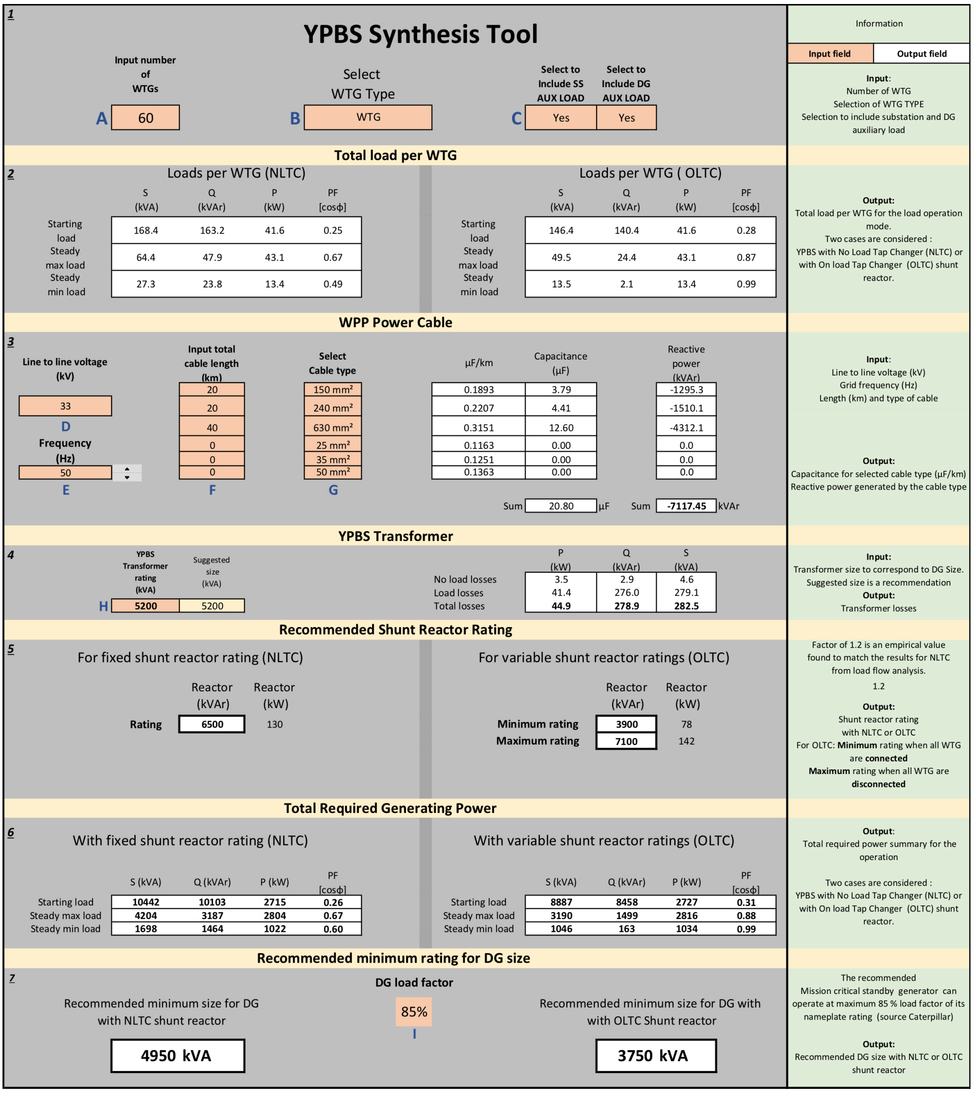


Figure 3.1: Main sheet of synthesis tool representing component data and recommended ratings of YPBS

3.1 Component data and loads

The synthesis tool includes the all the WTG models with YPBS support, in this report the component data is selected to correspond with the 4 MW WTG model loads and are used for calculations and simulations.

3.1.1 Yaw motor

The asynchronous motor data used in calculations and simulations is presented in table 3.1. The data is obtained from ABB Optimizer online tool [25] to correspond with the yaw motor ratings.

Table 3.1: Asynchronous motor data

Asynchronous motor		
Output power	2.7	[kW]
Supply voltage	400	[V]
Full load current	6.7	[A]
Starting current	25.46	[A]
Efficiency	80	[%]
Power Factor	0.8	
Full load rotational velocity	1300	[rpm]
Number of motors required to yaw	8	

3.1.2 WTG loads

When sizing the suitable DG and reactor, each load of the components in the WPP needs to be identified if they are active during power backup supply mode. WTG component loads are the most challenging to obtain since for many components, it is unknown if they are active during power backup supply mode. The synthesis tool will consider the minimum required WTG load represented in 3.2 to estimate the component size for the YPBS. The WTG loads considered are the yaw motors, WTG auxiliary transformer losses, and no-load losses for the WTG transformer.

Table 3.2: Minimum required WTG load

Minimum WTG load	Units	S (kVA)	P (kW)	PF
Yaw motor	8	37.14	29.71	0.80
WTG aux transformer losses	1	1.80	1.80	1.00
WTG transformer losses	1	21.73	8.50	0.39
Total load		60.67	40.0	0.66

3.1.3 Substation and DG auxiliary loads

Other loads that impact the sizing of the YPBS components are substation (SS) auxiliary load and DG auxiliary load. SS auxiliary load needs to be considered when the supply is within the internal grid of the WPP and is proportional to the installed capacity. SS auxiliary load consists of computer systems, switchgears, batteries, heating system and electrical equipment. To include SS auxiliary load in calculations, a mean value has been calculated with the data from existing WPPs. The SS auxiliary data used for calculations are presented in table 3.3.

Table 3.3: SS aux load considered per WTG

	S (kVA)	P (kW)	Q (kVAr)
SS auxiliary load per WTG	3.75	3.06	2.15

The DG auxiliary load consists of cooling and ventilation (table 3.4), and will be considered in the calculations as a static load, independent of the DG size.

Table 3.4: DG auxiliary load

DG auxiliary load	S (kVA)	P (kW)	PF
Cooling	37.50	30.0	0.80
Ventilation	18.75	15.0	0.80
Total load	56.25	45.0	0.80

3.2 Synthesis tool calculations

The purpose of this section is to illustrate in detail the loads considered and assumptions made in order to get a preliminary component rating for the YPBS. The following calculations are for starting and running operating conditions, where running condition is divided in two parts, steady max load and steady min load. Starting condition considers the inrush current for the energization of the yaw motors, transformer losses and auxiliary load. Steady max load considers the full load current for the yaw motors, transformer losses and auxiliary loads. In steady min load the yaw motors are not active, only the transformer losses and auxiliary loads are considered. For all operating load conditions, the YPB transformer losses will change to correspond with the DG ratings, based on power losses ratio from transformers in the range of 1000 - 3500 kVA.

A detailed calculation of the operating load conditions is presented considering that a shunt reactor is utilized in the YPBS with NLTC. In order for the DG to operate within its stability operating limits all the components with active and reactive power must be taken into consideration when NLTC is applied. Table 3.5 presents an overview for calculation methods and loads considered. A summary of operating load conditions is presented when a variable shunt reactor with OLTC is utilized in the YPBS instead of a NLTC. The main difference is excluding the inductive reactive part of components in the operating loads for the generator to supply. The inductive reactive power of components together with the variable shunt reactor will compensate for the capacitive reactive power from the cables for all operating modes.

Table 3.5: Operating load condition

Operating load condition	Syntesis tool considers the following for the operating load conditions:
Starting load	• Inrush current and supply voltage to calculate starting power. • Starting PF for yaw motors at 0.2 lagging • WTG transformer no-load transformer losses • SS auxiliary loads • DG auxiliary loads • YPB transformer no-load and load losses • Shunt reactor losses (kW)
Steady max load	• Full load current and supply voltage to calculate the running power. • Running PF for yaw motors at 0.8 lagging • WTG transformer no-load transformer losses • SS auxiliary loads • DG auxiliary loads • YPB transformer no-load and load losses • Shunt reactor losses (kW)
Steady max load	• WTG transformer no-load transformer losses • YPB transformer no-load and load losses • SS auxiliary loads • DG auxiliary loads • Shunt reactor losses (kW)

3.2.1 Reactor sizing

The reactive power generated from the underground power cables is calculated by the equation 3.1.

$$Q_{Cables} = -2\pi f \cdot \ C \cdot \ l \cdot {U_{LL}}^2 \ \ [VAr] \tag{3.1}$$

$$U_{LL} \ = \ line\ to\ line\ voltage\ (V)$$

$$C = \ capacitance\ of\ the\ cables\ (\mu F/km)$$

$$l = total\ length\ of\ the\ cables\ (km)$$

$$f = frequency\ (Hz)$$

A shunt reactor is required to compensate for the capacitive reactive power generated by the MV internal cable collector grid. A part of the capacitive reactive power will be compensated from the transformers inductive reactive losses. The shunt reactor ratings are based on the operating load condition in the WPP. For maximum load condition, when all the WTGs are connected the minimum rating of the shunt reactor is required, for no-load condition when all the WTGs are disconnected the maximum rating of the shunt reactor is required.

$$Q_{Min\_rating} = -Q_{Cables} - Q_{YPB\_trafo} \ - \sum_{i=1}^{n} \ Qi_{WTG\_trafo\_no-load} \ \ [VAr] \tag{3.2}$$

$$Q_{Max\_rating} = -Q_{Cables} - Q_{YPB\_trafo\_no-load} \ [VAr] \tag{3.3}$$

When all the WTGs are connected, the minimum rating for the reactor is calculated as the total reactive power generated by the cables subtracting the reactive consumption from the YPBS transformer (no-load and load losses) and WTG transformers (no-load losses). WTG load is a fraction of the total WTG transformer capacity during power backup supply and therefore only the no-load losses are considered. At the no-load condition when all the WTGs are disconnected, the maximum rating for the reactor is calculated as the total reactive power generated by the cables subtracting reactive consumption from the YPBS transformer. Rating of shunt reactor depends on what type of tap changer is applied and considering the DG operating points to be within the stability limits.

3.2.2 Starting load with NLTC

The following calculations are with detailed steps for sizing the required DG for starting load.

1. The starting load for one WTG with eight yaw motors:

   The apparent power (kVA) for yaw motor starting load (SKVA) is determined by the supply voltage and inrush current from table 3.1.

   $$SKVA = 8 \cdot 25.46A \cdot 400V \cdot \sqrt{3} = 141.11\ kVA$$

   The PF for the DOL motor starting method is up to 0.2 lagging [19]. Active and reactive power for starting load of eight yaw motors:

   $$P_{yaw\_inrush} = SKVA \cdot starting\ PF\ = 141.11 \cdot 0.2 = 28.22\ kW$$

   $$Q_{yaw\_inrush} = \sqrt{SKVA^{\ 2} - P_{yaw\_inrush}{}^{2}} = 138.26\ kVAr$$

2. Total Starting kVA (TSKVA) per WTG is calculated considering yaw motors, WTG transformer losses (table 3.2) and SS auxiliary (AUX) load (table 3.3). Instead of adding the sum of active and reactive power for each component to compute the new apparent power. Present apparent power value is added together to represent a worst case scenario for the loads.

   $$TSKVA = SKVA + S_{WTG_{Trafo}} + S_{\mathrm{SS}_{AUX}}$$

   $$TSKVA = 141.11\ + 23.53 + 3.75 = 168.39\ kVA$$

   Active and reactive power for total starting load per WTG:

   $$P_{start} = P_{yaw\_inrush} + P_{WTG_{Trafo}} + P_{\mathrm{SS}_{AUX}} =\ 28.22 + 10.3 + 3.06\ = 41.59\ kW$$

   $$Q_{start} = \sqrt{TSKVA^{\ 2} - P_{start}{}^{2}} = 163.17\ kVAr$$

3. The total required generator kVA (TGKVA) for the WPP is calculated considering the total number of WTGs, TSKVA, DG auxiliary load (table 3.4) and YPB transformer.

   $$TGKVA = NbrOfWTGs \cdot TSKVA\ + S_{DG_{AUX}} +\ \mathrm{S}_{\mathrm{YPB}_{\mathrm{Trafo}}}$$

   For a WPP with one WTG the total required generating power:

   $$TGKVA = 1\ WTG \cdot 168.39 \frac{kVA}{WTG} + 56.25\ kVA + 5.4 kVA = 230\ \ kVA$$

   $$P_{gen}\ =\ 1\ WTG \cdot P_{start} + P_{DG_{AUX}} + P_{YPB_{Trafo}} = 41.59 + 45 + 0.9 = 87.4\ \ kVA$$

   $$Q_{gen} = \sqrt{\mathrm{TGKVA}^2 - P_{gen}{}^{2}} = 212.7\ kVAr$$

3.2.3 Steady max load with NLTC

Steady max load considers that all yaw motors are in running operating condition. Apparent power for running yaw motor is determined by the supply voltage and full load current from table 3.1. The following calculations are with detailed steps for sizing the DG for steady max load.

1. The running load for eight yaw motors:

$$S_{yaw} = 8 \cdot 6.7\ A \cdot 400V \cdot \sqrt{3} = 37.14\ kVA$$

$$P_{yaw} = S_{yaw} \cdot PF\ = 37.14 \cdot 0.8 = 29.71\ kW$$

$$Q_{yaw} = \sqrt{SKVA^{\ 2} - (P_{yaw})^2} = 22.28\ \ kVAr$$

2. Total Runing KVA (TRKVA) per WTG is calculated considering yaw motors, WTG transformer losses and SS auxiliary load. The apparent power is added together to represent a worst case scenario for the loads.

$$TRKVA = S_{yaw} + S_{WTG_{Trafo}} + S_{\mathrm{SS}_{AUX}}$$

$$TRKVA = 37.14\ + 23.53 + 3.75 = 64.42\ kVA$$

Active and reactive power for TRKVA per WTG:

$$P_{running} = P_{yaw} + P_{WTG_{Trafo}} + P_{\mathrm{SS}_{AUX}} =\ 29.71 + 10.3 + 3.06\ = 43.07\ kW$$

$$Q_{running} = \sqrt{TRKVA^{\ 2} - P_{running}{}^2} = 47.90\ kVAr$$

3. TGKVA for the WPP is calculated considering the total number of WTGs, TRKVA, DG auxiliary load and YPB transformer.

$$TGKVA = NbrOfWTG \cdot TRKVA + S_{DG_{AUX}} + \mathrm{S}_{\mathrm{YPB}_{\mathrm{Trafo}}}$$

For a WPP with one WTG the total required generating power:

$$TGKVA = 1\ WTG \cdot 64.42\frac{kVA}{WTG} + 56.25\ kVA + 5.4kVA = 126\ \ kVA$$

$$P_{gen}\ =\ 1\ WTG_{running} + P_{DG_{AUX}} + P_{YPB_{Trafo}} = 43.07 + 45 + 0.8 = 89\ kVA$$

$$Q_{gen} = \sqrt{\mathrm{TGKVA}^2 - P_{gen}{}^2} = 89\ kVAr$$

3.2.4 Steady min load with NLTC

Steady min load considers standby consumption and is defined by transformer losses and auxiliary loads.

1. Steady min load per WTG will include the WTG transformers and SS auxiliary load

$$S_{min} = S_{WTG_{Trafo}} + S_{SS\_Aux} = 23.53 + 3.75 = 27.28 \;\; kVA$$
$$P_{min} \;\; = P_{WTG_{Trafo}} + \;\; P_{SS\_Aux} = 10.3 + 3.06 = 13.36 \; kW$$
$$Q_{min} = \;\; \sqrt{{S_{min}}^2 - {P_{min}}^2} \;\; = 23.78 \; kVAr$$

2. TGKVA for the WPP is calculated considering the total number of WTGs, DG auxiliary load and YPB transformer losses.

$$TGKVA = NbrOfWTG \cdot S_{min} + S_{DG_{AUX}} + \mathrm{S}_{\mathrm{YPB}_{\mathrm{Trafo}}}$$

For a WPP with one WTG the total required generating power required:

$$TGKVA = 1 \; WTG \cdot 27.28 \frac{kVA}{WTG} + 56.25 \; kVA + 0.1kVA = 83.63 \; kVA$$
$$P_{gen} \;\; = \;\; 1 \; WTG \cdot P_{min} + P_{DG_{AUX}} + P_{YPB_{Trafo}} = 13.36 + 45 + 0.9 = 59.26 \; kVA$$
$$Q_{gen} = \;\; \sqrt{\mathrm{TGKVA}^2 - {P_{gen}}^2} \;\; = 59 \; kVAr$$

3.2.5 Summary of load conditions and recommended DG rating with NLTC

Table 3.6: Load per WTG for starting and running condition (NLTC)

Load per WTG	S (kVA)	P (kW)	Q (kVAr)	PF
Starting load	168.39	41.59	163.17	0.25
Steady max load	64.42	43.07	47.90	0.67
Steady min load	27.28	13.36	23.78	0.49

Table 3.7: TGKVA and DG rating for selected WPPs (NLTC)

Number of WTGs	TGKVA Starting load (kVA)	TGKVA Steady max load (kVA)	TGKVA Steady min load (kVA)	Recommended DG rating (kVA)
1	230	126	84	150
6	1094	470	220	550
12	2131	884	385	1050
18	3169	1297	549	1550
30	5249	2130	877	2500
42	7324	2957	1205	3500
60	10442	4204	1698	4950
160	27744	11107	4433	13050
200	34670	13874	5528	16300

$$Recommended\ DG\ rating = \frac{Steady\ max\ load}{0.85}$$

A validation for the sizing of the DG is done in Caterpillar SpecSizer[1] [26] in section 4.3 and load flow simulations in section 4.1 to validate if the DG operating points are within the stable region of the capability chart. The recommended DG rating is based on the steady max load due to validation that the DG size can be less than starting load requirement, further discussed in section 4.3. Misson critical ESP gensets are designed to operate at maximum 85 % load of its capacity [9].

[1] SpecSizer is a web-based software tool that suggest appropriate generator size based on site parameters and load characteristics

3.2.6 Summary of load conditions and recommended DG rating with OLTC

Operating loads per WTG with OLTC is presented in table 3.8 and recommened DG rating for selected WPPs are presented in table 3.9. The main difference in the calculations is excluding the inductive reactive part of components in the operating loads for the DG to supply, resulting in a DG that operates with higher PF and less requird installed capacity. The inductive reactive power of components together with the variable shunt reactor will compensate for the capacitive reactive power from the power cables during all operating load conditions. When comparing table 3.6 to table 3.8 for steady max load, the difference in PF for excluding the reactive power losses for the WTG transformers has increased from 0.67 to 0.87. This results in a more efficient operation of a power system, the reactive power flow is minimized and mainly active power is generated.

Table 3.8: Load per WTG for starting and running (OLTC)

Load per WTG	S (kVA)	P (kW)	Q (kVAr)	PF
Starting load	147.32	41.59	141.33	0.28
Steady max load	49.52	43.07	24.43	0.87
Steady min load	13.53	13.36	2.15	0.99

Table 3.9: TGKVA and recommended DG size for selected WPPs (OLTC)

Number of WTGs	TGKVA Starting load (kVA)	TGKVA Steady max load (kVA)	TGKVA Steady min load (kVA)	Recommended DG rating (kVA)
1	197	108	71	150
6	936	369	151	450
12	1825	682	249	800
18	2714	996	349	1150
30	4493	1623	548	1900
42	6271	2250	748	2650
60	8939	3190	1046	3750
160	23762	8414	2707	9900
200	29691	10505	3372	12350

3.3 Simulations

The software used for the simulations of the electrical grid is DIgSILENT PowerFactory [27]. PowerFactory is an analysis software application for electrical power systems. The software is a computer aided engineering tool for analysing generation, transmission and distribution in electrical power systems. The simulations conducted in PowerFactory are load flow analysis [2], the analysis will investigate the requirements for the power system operation under normal three-phase steady state conditions. PowerFactory computes the voltage magnitude and angle at each bus and power flows for all interconnections in the grid.

The requirements for steady state condition:

- Synchronous generator to operate within its capability chart for active and reactive power limits
- Synchronous generator supplies power to the demand for loads and losses
- Bus voltage magnitude to remain close to rated values
- Collector cable network and transformers are not overloaded

The software was learned by studying the manual [28] and completing the tutorial exercises [29]. The tutorial illustrates the steps required to design a project with power system components and to perform load flow studies.

[2] Load flow or power flow study is an analysis of the power system network, to determine the steady state operating characteristics

3.3.1 Model

DIgSILENT PowerFactory version 18.0.9 is used to create the network model for each WPP. The model includes the following power system components:

- YPB generator
- YPB transformer
- Shunt reactor
- Internal collector cable network
- WTG transformer
- WTG load
- SS auxiliary transformer
- SS auxiliary load
- DG auxiliary load

The model for WPPs consist of 6-60 WTGs, there are ten feeders in total and each feeder consists of six WTGs. Figure 3.2 illustrates a WPP model with six WTGs. Each feeder has an underground cable with data and total length presented in table 3.10. The WTG loads (table 3.2) is connected to 33 kV busbar through an 0.72/33 kV WTG transformer. The WTG auxiliary transformer losses are modelled as low voltage static WTG load. The DG is connected to 33 kV busbar through an 0.69/33 kV YPB step-up transformer. The shunt reactor is connected directly on the 33 kV busbar. The SS transformer from MV to HV is not modelled since it is not required, the only power generating source is the DG when the grid is disconnected.

Table 3.10: Collector network cable data used in simulations

Cable data 33 kV @50 Hz	Resistance (Ω/km)	Reactance (Ω/km)	Capacitance $(\mu F/km)$	Ampacity (A)	Length per feeder (km)
3x150 mm^2	0.265	0.127	0.189	320	2
3x240 mm^2	0.161	0.117	0.221	415	2
3x630 mm^2	0.0629	0.102	0.315	690	4

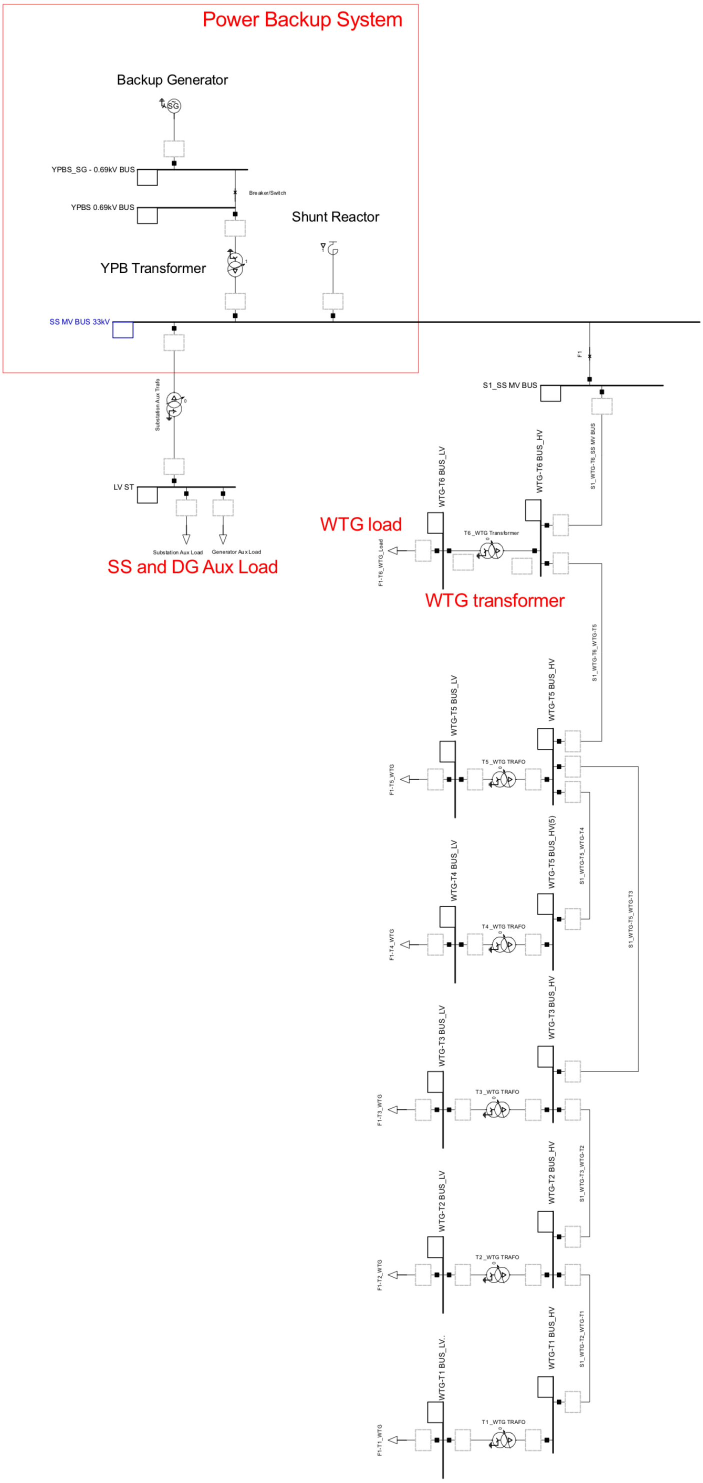


Figure 3.2: WPP PowerFactory model with six WTGs

3.3.2 YPBS component sizing from synthesis tool

The selected WPPs with 6-60 WTGs and recommended ratings for DG and shunt reactor with NLTC and OLTC applied, are obtained from synthesis tool and presented in table 3.11. The collector network cable data used both in simulations are presented in table 3.10. Shunt reactor with NLTC will have fixed rating for both conditions. Shunt reactor with OLTC has minimum rating when in load condition and maximum rating when in no-load condition.

Table 3.11: Recommended DG and shunt reactor ratings for six WPPs

Number of WTG	DG rating (NLTC) (kVA)	Shunt reactor rating (NLTC) (kVAr)	DG rating (OLTC) (kVA)	Minimum shunt reactor rating (OLTC) (kVAr)	Maximum shunt reactor rating (OLTC) (kVAr)
6	**550**	650	**450**	350	700
12	**1050**	1300	**800**	750	1400
18	**1550**	1950	**1150**	1150	2150
30	**2500**	3250	**1900**	2700	3550
42	**3500**	4550	**2650**	2750	5000
60	**4950**	6500	**3750**	3900	7100

3.3.3 Method

For each WPP from table 3.11, two scenarios are investigated, with NLTC or OLTC applied. For each scenario two operation conditions have been investigated that represent maximum load and no-load condition. The first condition will consider that all the WTGs must be able to yaw simultaneously, resulting in max load for supply of total demand. Second condition represents a no-load condition where all the WTGs are disconnected. During no-load condition the DG should be allowed to operate at maximum -0.25 per-unit and during maximum load conditions beneath 0.9 per-unit, to operate inside of the reactive power limits (figure 2.5). The DG should operate within the stability region for both operating conditions to ensure safety.

3.4 Sequential starting of yaw motors

The DG should be sized considering starting capabilities defined by applied component load and the allowable instantaneous voltage dip within the power network system[18]. Figure 3.3 illustrates that simultaneous starting of all yaw motors impacts the DG size by a factor of 2.5 relative to steady max load and by a factor of 6.3 relative to steady min load. Sizing after starting capabilities would in most cases result in an oversized DG where the steady load is under 30 % of the DG load factor. Running at light load for prolonged runtime would result in negative effect to the DG [9].

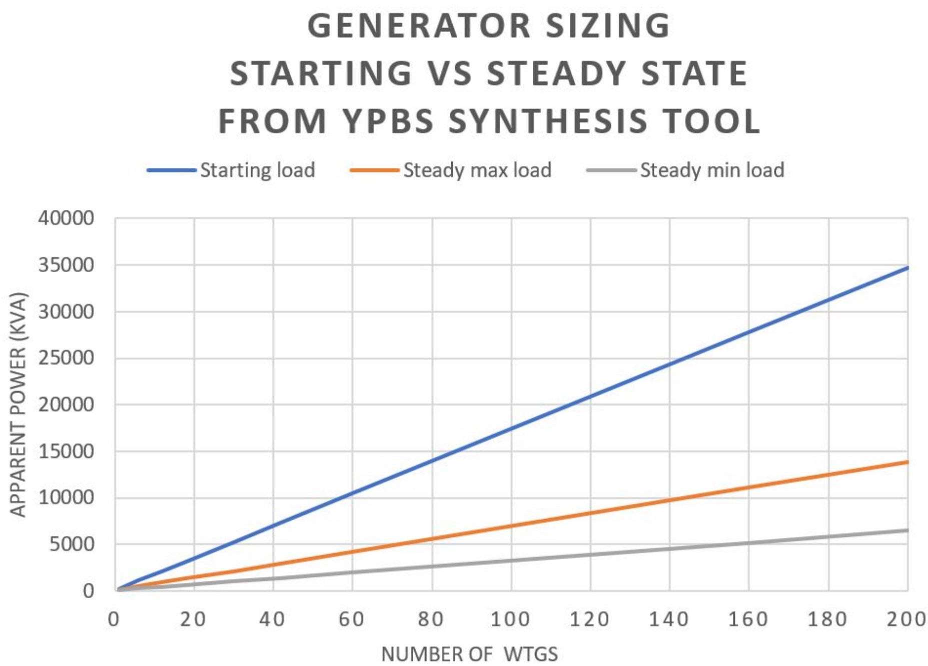


Figure 3.3: TGKVA requirement for starting vs steady load from table 3.7 (NLTC)

A solution to make the sizing more cost efficient is to implement sequential starting for the yaw motors, by energizing the feeders in steps. A WPP with 18 WTGs will be analysed for the impact of the DG size with sequential starting of the yaw motors.

3.4.1 Case description and data used for sequential starting study

Caterpillar's online genset sizing software SpecSizer will be used for analysing the required DG size for sequential starting of the yaw motors. The objective is to validate the impact of the DG size when sequentially energizing the yaw motors. The following data is used as input for the three cases and the case sizing report from SpecSizer are presented in section A as appendices.

- 8 yaw motors with output power of 2.7 kW each per WTG
- 18 WTGs with a total of 144 yaw motors
- Three feeders with 6 WTGs per feeder
- Permitted frequency dip 5 %
- Permitted voltage dip 15 %
- Starting method: Direct-On-Line (DOL)
- Assuming that motors are starting under load
- DOL starting PF = 0.2
- Running PF = 0.8
- Generator PF = 0.8

SKVA for one yaw motor, data derived from table 3.1:

$$SKVA_{oneyawmotor} = \sqrt{3} \cdot 400\ V \cdot 25.56\ A = 17.64\ kVA$$

SKVA for 48 yaw motors representing 6 WTGs per feeder:

$$SKVA_{feeder} = 48 \cdot 17.64 = 846\ kVA$$

The first case represents a simultaneous start of the 144 yaw motors for the respective 18 WTGs in feeder 1, 2 and 3. Case two is divided into two steps. The first step, yaw motors for 12 WTGs will simultaneous be starting in feeder 1 and 2. In the second step the remaining yaw motors for the 6 WTGs in feeder 3 will be started while supplying the required running power for the 12 WTGs in feeder 1 and 2. Case three is divided into three steps, where each step will start motors at one feeder at a time and supply running power to the already energized motors in the previous feeder.

4. Results and discussions

This section will present results from load flow analysis in PowerFactory with sizing of DG and reactor recommended from synthesis tool, and sequential motor starting analysis results from Caterpillar SpecSizer.

4.1 Load flow summary with NLTC applied

Table 4.1: Load flow summary with NLTC applied

Study Case	WTGs connected	SS Load (kW)	DG Aux Load (kW)	**DG (kVA)**	DG operating (kW)	DG operating (kVAr)	Total Load (kW)	Total Load (kVar)	**Shunt Reactor (kVAr)**	Shunt Reactor operating (kVAr)	Shunt Reactor operating (kW)	Line charging (kVAr)
1	6	25	45	**550**	328	305	260	190	**650**	599	120	-640
2	0	15	45	**550**	78	-17	60	40	**650**	684	14	-750
3	12	45	45	**1050**	605	564	470	340	**1300**	1202	24	-1310
4	0	20	45	**1050**	100	-79	60	50	**1300**	1382	28	-1510
5	18	70	45	**1550**	884	827	680	500	**1950**	1803	36	-1950
6	0	35	45	**1550**	129	-134	80	60	**1950**	2077	42	-2280
7	30	100	45	**2500**	1417	1341	1090	800	**3250**	3022	60	-3290
8	0	50	45	**2500**	174	-255	100	70	**3250**	3476	70	-3810
9	42	160	45	**3500**	1977	1881	1530	1120	**4550**	4256	85	-4700
10	0	80	45	**3500**	232	-363	130	90	**4550**	4870	97	-5360
11	60	200	45	**4950**	2769	2649	2140	1560	**6500**	6085	122	-6670
12	0	100	45	**4950**	297	-546	150	110	**6500**	6971	139	-7510

The following load flow analysis results represent minimum WTG load (table 3.2) with DG and reactor size recommended from YPBS synthesis tool (NLTC) as shown in table 3.11. During maximum load condition when all the WTGs are connected the DG will operate with lagging PF, and is generating more reactive power then the total required load in the WPP. This indicates that the shunt reactor rating is greater than required and the DG is generating reactive power to compensate for the inductive reactive power generated by the shunt reactor. At no-load condition when the WTG load and transformers are disconnected the DG is operating with leading PF, absorbing reactive power due to the capacitance of the underground cables dominating the inductive load. The dominating capacitive reactive power is increasing the grid voltage illustrated by the load flow summary. Reactive power is greater for shunt reactor and line charging during no-load condition due to the increased voltage. For maximum load the inductive reactive power dominates and the voltage is decreased lower than 1 per-unit resulting in lower ratings for reactor and line charging. The result indicated that a shunt reactor with less size than recommended can be applied in maximum load condition and a greater size than recommended can be applied at no load condition. Utilizing a reactor with less ratings during maximum load condition would result in a DG with higher PF and with less required installed capacity. However during no-load conditions the reactor is undersized, the DG will need to absorb more reactive power to compensate for the capacitive reactive power and will operate outside the operation limit of -0.25 per-unit. Due to NLTC the windings need to be de-energized before any adjustment can be done before changing the rating of the reactor. During operation this procedure is not feasible, resulting in a reactor that is required to have a fixed rating for both operating conditions.

Even though the DG is operating with lower PF then optimal, the results in figure 4.1 illustrate that operating points for all study cases are within the capability curve. The DG loading factor is above 50% of installed capacity for maximum load and fills the requirement of prolonged runtime from underloading [9].

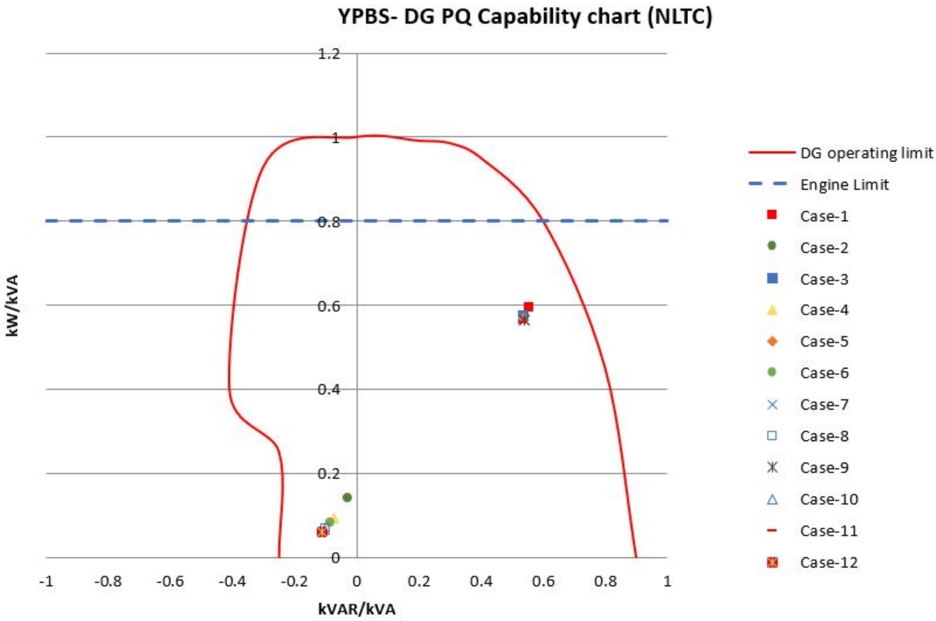


Figure 4.1: DG capability chart with study case 1-12 from table 4.1

4.2 Load flow summary with OLTC applied

Table 4.2: Load flow summary with OLTC applied

Load flow summary with OLTC applied												
Study Case	WTGs connected	SS Load (kW)	DG Aux Load (kW)	**DG (kVA)**	DG operating (kW)	DG operating (kVAr)	Total Load (kW)	Total Load (kVar)	**Shunt Reactor (kVAr)**	Shunt Reactor operating (kVAr)	Shunt Reactor operating (kW)	Line charging (kVAr)
1	6	25	45	**450**	327	-6	260	190	**350**	359	7	-730
2	0	15	45	**450**	78	36	60	40	**700**	719	14	-730
3	12	45	45	**800**	599	-7	470	340	**750**	779	16	-1480
4	0	20	45	**800**	98	27	70	50	**1400**	1457	29	-1480
5	18	70	45	**1150**	881	5	680	500	**1150**	1182	24	-2200
6	0	35	45	**1150**	132	79	80	60	**2150**	2221	44	-2200
7	30	100	45	**1900**	1417	-4	1090	800	**2700**	2012	40	-3670
8	0	50	45	**1900**	176	65	100	70	**3550**	3694	74	-3710
9	42	160	45	**2650**	1980	12	1530	1120	**2750**	2853	57	-5170
10	0	80	45	**2650**	236	115	130	90	**5000**	5197	104	-5180
11	60	200	45	**3750**	2782	-63	2140	1560	**3900**	4068	81	-7430
12	0	100	45	**3750**	305	93	150	110	**7100**	7410	148	-7430

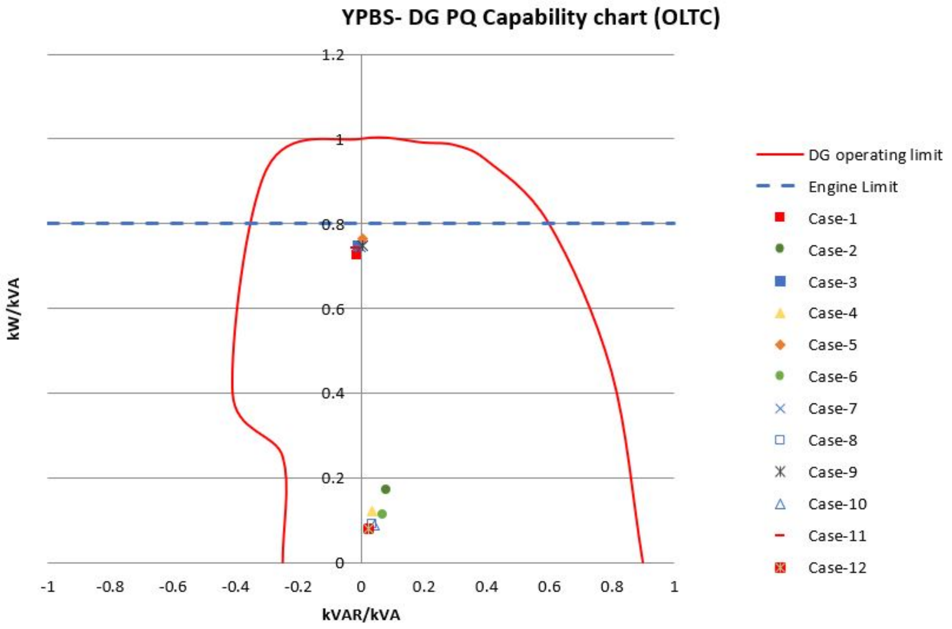


Figure 4.2: DG Capability chart with study case 1-12 from table 4.2

The following load flow analysis results represent minimum WTG load (table 3.2) with DG and reactor size recommended from YPBS synthesis tool for OLTC as shown in table 3.11. During maximum load condition the total inductive reactive power in the WPP is compensating for the capacitive reactive power generated by the underground cables. Resulting in a DG that is generating mainly active power and operating below the engine limit operation point at 0.8 per-unit with margins for all study cases. During no-load conditions when the WTG load and transformer are disconnected the shunt reactor size is adequate to compensate for the line capacitance. The grid voltage is almost constant for both operating conditions. The results illustrate that operating points for all study cases are within the capability curve (figure 4.2) and the DG is operating above 70% of installed capacity for maximum load, fulfilling the requirement of prolonged runtime from underloading [9].

4.3 Sequential starting of yaw motors

Summary of the results for sequential starting are presented in table 4.3 and the SpecSizer project reports are presented as appendices in section A. The size of the DG could decrease by a factor of 2.4 if the starting of the yaw motors is divided in three steps instead of one, represented in Case 1 (A.1) and Case 3 (A.3). Sequential starting reduces the total inrush current for the starting phase of the yaw motors. A DG of less size can be selected that operates greater than 50 % of its capacity when the motors are in running mode. As the cost of the DG is relative to its size, a reduction of the DG by a factor of 2.4 would decrease the cost approximately at the same rate.

Table 4.3: Summary of sequential start of yaw motor

Load step analysis from SpecSizer	DG rating (kVA)	Maximum transient peak (kVA)	Final running load (kVA)	DG capacity used (%)	Predicted frequency dip (%)	Predicted voltage dip (%)	Typical recovery time (seconds)
Case 1	1825	2538.7	607.5	33.5%	3.0%	14.4%	6.8
Case 2	1150	1692.5	607.5	52.8%	2.8%	14.5%	6.2
Case 3	770	1180.2	607.5	79.1%	3.8%	14.6%	4.5

A WPP with 18 WTG has steady state rating at maximum 1297 kVA (table 3.7) where the instantaneous starting of all yaw motors has maximum transient at 2539 kVA, illustrated in Case 1. SpecSizer is suggesting a DG size at 1825 kVA for starting the yaw motors at once or 770 kVA for starting the yaw motors in three steps. For the recommended DG, the typical transient recovery when applying an instantaneous load change of 1 per-unit (block load) would take about 4.5-6.8 seconds. If the start-up sequence of yaw motors is managed in steps, the task of starting all yaw motors would be achieved within 12.4 seconds (Case 2 A.2) or 13.5 seconds (Case 3). Although the block load transient responses are with factory conditions representing a typical Caterpillar generator set, the time frame for starting all yaw motors at once or in three steps is at most two times greater. If this time interval is acceptable, depending on how the sequential steps are implemented the DG can be reduced in size resulting in significant cost reduction and resulting in a DG that operates at 50-80 % of installed capacity and fulfilling the requirements from underloading [9]. For all three cases the voltage dip is under 15 % and frequency dip under 5 % validating that the starting power of yaw motors could exceed the rating of DG. This indicates that a DG could be sized based on steady max load ratings. The following assumption considers the starting of yaw motor load assuming the WTG transformer is already energised.

4.4 Discussions

The suggested DG and reactor ratings for NLTC and OLTC indicate that YPBS synthesis tool can be used for the initialization phase of YPBS projects. All study cases with the suggested ratings are operating within the capability limits providing safety to the components. The load flow analysis and studies for sequential starting of yaw motors illustrates some of the factors that will impact the operation, sizing and cost of the components. From SpecSizer project sizing reports, it can be concluded that the installed capacity of DG can be less in size than the total starting power of the yaw motors. Indicating that a DG can be sized after the maximum steady state load requirements, which brings significant cost reduction. Additional size reduction can be achieved by implementing sequential starting and starting the yaw motors in several steps instead of simultaneously starting all the yaw motors in one step. The results have illustrated that DG size can be decreased by a factor of 2.4, when applying sequential starting. Resulting in cost reduction at approximately the same rate.

This concept of sequential starting must be further verified in Electromagnetic Transient (EMT) studies to consider the transformers inrush current when switching on the breaker for each feeder. Although, according to [19] the transformer inrush current is less in magnitude when supply is from a genset and is generally in line with the full load current.

Further cost reduction can be achieved by parallel coupling of multiple gensets of less size. Paralleling genset systems have been proven to provide price competitive solutions and reduce the upfront cost of the system [30]. From load flow analysis it can be concluded that DG size is 30 % greater when utilizing a shunt reactor with fixed ratings instead of one with variable ratings. This difference is due to restrictions of fixed rating shunt reactors, the DG will have to supply or absorb more reactive power during varying load conditions, resulting in a larger DG size. When a variable shunt reactor is applied, the DG will operate more efficiently generating mainly active.

5. Responsibility matrix

Successful project management begins by planning and defining the project objectives into deliverable manageable sections to provide a foundation and establish a framework. The Work Breakdown Structure (WBS) is used early in planning to define the project scope of work and to break down large tasks into manageable sections of work that can be easily supervised and estimated. Most WBS consists of multi-level hierarchy describing the project work and captures all deliverables, internal and external for the completion of the work [31]. Each of the WBS sections is dedicated to the responsibilities of the stakeholders, in the various deliverables for the project. Stakeholder is either an individual, group or organization that has an interest in the project outcome and is linked to the WBS sections through the Responsibility Assignment Matrix (RAM). RAM is a chart with a simple structure to describe the stakeholder participation for each specific WBS section. RAM is implemented to define roles and responsibilities with clear understanding of expectations, where every task is mapped preventing over or under allocation of resources and delays. The RAM brings structure and clarity and provides a model for effective communication between the roles. The RAM has several model types depending on implementation although the RACI matrix model is used for general practice in project management.

5.1 RACI matrix

The RACI matrix is a tool for highlighting roles and responsibilities during a project and the acronym stands for Responsible, Accountable, Consulted and Informed.Each representing a level of responsibility for a work section. The tool identifies functional areas, activities and decision points enabling the management to clarify the responsibility for each stakeholder. A sample of RAM using the RACI model is illustrated in table 5.1 adopted from [32]. The matrix presents the work to be done for the WBS sections as activities associated with stakeholders as individuals.

Table 5.1: RAM using RACI model

Activity \ Person	Ann	Ben	Carlos	Dina
Requirements	R	C	A	I
Design	A	R	I	C
Develop	I	A	R	C
Test	I	R	R	A

- The Responsible role, the stakeholder is responsible for leading and delivering the task to completion. There is at least one role with the participation type of responsible in the activities. When several stakeholder's share the responsible role there is a need to clarify who is the key responsible. The responsible role ensures that deliverable is done with the support of the other nominated stakeholders to the point where the accountable role takes over for approval.
- The stakeholder with an accountable role is ultimately answerable for the completion and quality of the delivered task. There should only be one with the accountable role for each specific activity. The accountable role manage the implementation of the project and provide support to the responsible role. They give approval so that work can progress, and are the final approving authority.
- The Consultant role are advisers and experts for the subject in matter and provides information that adds value to the defined activity or project. Their contribution adds quality to the decision making and enables the responsible to execute the task more efficiently.
- The informed role are stakeholders that need to be informed and kept up to date on the progress of work for the specific section but are not involved in the actual decision making. The communication is one way between the informed role and the other stakeholders.

5.2 YPBS WBS

The first step for creating a RACI matrix is to identify the requirements and objectives for each work section activity in the YPBS project. The WBS of the YPBS project will represent the execution and service phase, the work activities are illustrated in figure 5.1.

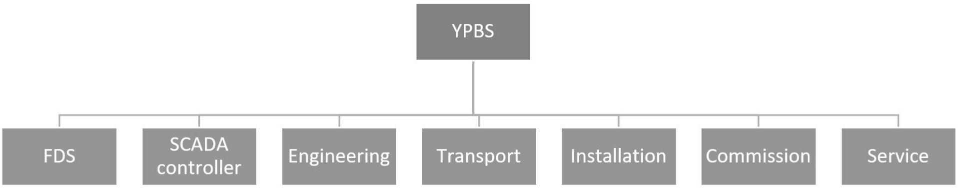


Figure 5.1: WBS for the YPBS project

- Functional Design Document (FDS): A complete document that specifies the site specific YPBS and components. FDS contains system overview, system analysis, technical description, design data of equipment, functional description of the system, detailed description about the energization and operational tasks.
- SCADA controller: Control design to provide communication, data and control for the YPBS integration with the WPP. SCADA is a computer system for monitoring the WPP by gathering and analysing real time data, the acronym stands for Supervisory Control and Data Acquisition.
- Engineering: Mostly civil engineering, concentrating on installation of foundation, pipeline and cables.
- Transport: Coordination of the transport for the YPBS components.
- Installation: Connection of the YPBS components to the SS building. Making sure that the communication interfaces are in place and all power cables are connected accordingly.
- Commissioning: Consists of tests to assure correct operation of the YPBS components.
- Service: Taking care of the operational tasks and service of the YPBS components.

5.3 YPBS stakeholder

The stakeholders involved in the YPBS project for execution and service phase are presented in figure 5.2.

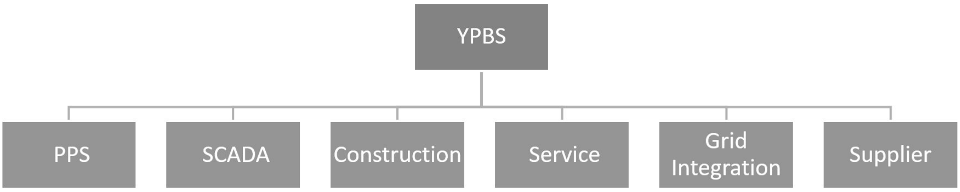


Figure 5.2: Stakeholders for YPBS project

- PPS - Power Plant Solutions is the team responsible for the electrical system during sales and construction, with focus on the grid. The team has the main responsibility of the electrical areas and to ensure that the deliveries of the electrical related task are being carried out.
- SCADA team provides solutions to implement the control system configuration. Leading the communication interface topics and make sure that the systems will be able to communicate with each other.
- Construction team is in control of the management and coordination of activities. The team has the overall responsibility of the activities on site. Coordinating the tasks and capturing the missing parts.
- Service team performs the maintenance of the components and the operational tasks when the construction phase has been finalized.
- Grid integration performs analysis of the grid and provides the YPBS components sizing. Observing the energization studies and carrying out the short circuit studies.
- Supplier designs and manufactures the YPBS components and delivers them to site. They make sure that requirements according to the agreements are met.

5.4 RACI for YPBS

For each activity a role needs to be identified and assigned. To achieve this, it is important to obtain knowledge and understand the roles of each stakeholders and how they can add value to the project. In this step, interviews were conducted with stakeholders to get their perspective on which of these activities they can perform or give support. The initial step was to create a RACI with a few stakeholders to identify the roles for each task and distribute the responsibilities. This approach with a few stakeholders involved was effective to get an agreement for creating a framework of the matrix. The initial version was introduced individually to the remaining stakeholders for their view and confirmation for each role to create the final version of RACI for the YPBS. A simplified version of the final matrix is presented in table 5.2.

Table 5.2: RACI for YPBS project

Activity \ Stakeholder	PPS	Scada	Construction	Service	GI	Supplier	Customer
FDS	R,A	I,C	I	I	C	I	I,C
Control System	C	R,A			I		I
Engineering	I,C		R,A	I		C	I,C
Transport	I		I			R,A	I,C
Installation	I,C		A	I		R	
Commission	C		A		I	R	R
Operation							R,A
Service	I,C			R,A		R	I,C

5.5 Discussions

The interviews provided educational information about the various departments and the roles they undertake for the specific project but also in general. The interviews gave important insights on distributing the matrix in more detailed steps of responsibility, to get the right people involved that can add value to specific tasks and who needs to be informed on the ongoing tasks to feel committed to the project. Stakeholders input during these interviews gave valuable information to define the tasks to a reasonable level for the possibility to easily have an overview of the assigned responsibilities. The workshops were challenging when stakeholders did not agree on the specific responsibility and changes had to be made to the distributed matrix. This made the distribution of responsibilities more challenging as it requires taking steps back to move forward. The already decided division of responsibilities would need to be discussed again with more stakeholders involved to settle the differences. These additional workshop gave a more in depth understanding of the each respective role of the stakeholder in the project, and this collaboration gave more strength to the responsibility matrix. It is difficult to know which approach is the most effective for starting and completing the matrix, although communication between stakeholders and information to understand the responsibilities and activities is crucial for creating the RACI.

6. Conclusions and future work

The synthesis tool provides reliable information for the initialization phase of the YPBS project and will be used as an official tool in Vestas. The responsibility matrix is created with the activities and corresponding responsibilities for the YPBS project. The matrix is agreed on by all involved stakeholders and will be implemented in future projects. The simulation study cases with recommended ratings from the tool, indicates that the YPBS components are operating within their stability limits and fulfilling operation requirements. The studies include different sizes and models of the WPP with NLTC or OLTC applied. When a variable shunt reactor with OLTC is applied, the DG will operate more efficiently and the installed capacity can be reduced by 25 %. The results from sequential starting analysis illustrates that the maximum steady load condition can be considered when sizing the DG. Sizing the DG after the starting load condition would result in a prolonged runtime of under-loading and would make the sizing unfeasible, especially for a large WPP. Implementing sequential starting of the yaw motors would reduce the inrush transient and result in a reduction of the DG size by a factor of 2.4. Resulting in cost reduction at approximately the same rate. Further cost reduction can be achieved by parallel coupling of multiple gensets of less size. Utilizing a variable shunt reactor with OLTC is recommended for dynamic compensation for present operation requirements but also for flexibility of future load conditions. However, the mechanism of OLTC is more complex than NLTC. Dynamic transient studies need to verify if the DG can operate safely and not trip during the energization of the reactor when the tap changers are switching windings during varying load conditions. A genset is required to supply a mixture of power loads, applications with an asynchronous motor present and energization of the components are the most challenging factors for genset sizing. Future work for the YPBS project:

- Create a detailed model of the DG with AVR and governor
- Perform dynamic transient simulations to evaluate the performance and behaviour of the DG, due to energization of the transformers, shunt reactor, cable arrays, loads and the asynchronous motors.
- Design the energization sequence in relation to the dynamic behaviour of the components that is producing the least disruption to the DG operation.

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A. Project sizing report from SpecSizer

Following section contains sizing report with suggested generator from SpecSizer, representing sequential starting case 1, 2 and 3 (4.3).

A.1 Sequential starting case 1

Case 1 represents all yaw motors in the 18 WTGs starting simultaneously resulting in highest transient inrush.

CAT Project Sizing Report			
Project Name	WPP with 18 WTGs 1step	Electricity Supply	50 Hz 400/230 V
Customer Name		Connection	STAR
Region	EAME/CIS	Max. Ambient Temperature	77.0 F
Prepared By	Vigan Spahiu	Altitude	500.0 Ft. A.S.L
Modified Date	6-May-2020	Humidity	30%
Load Analysis Summary			
Max Transient Load Step	2,538.7 SkVA / 507.7 SkW		
Peak Transient Load Step	2,538.7 SkVA / 507.7 SkW		
Final Running Load	607.5 kVA / 486.0 kW / 0.80 PF		
Max Running Non Linear Load	0.0 RkVA		
Maximum Running Load	607.5 kVA / 486.0 kW		
Selection Criteria	Step 1 Voltage dip restriction		
Generator Set			
Generator Set Model	(1) of 3516	Nameplate Rating	1,460.0 ekW / 1,825.0 kVA / 0.8 PF
Voltage Regulator and Slope	CDVR 2:1 slope;	Site Output Rating	1,451.8 ekW / 1,814.7 kVA
Feature Code	516DRL5	Rating Type	Prime
Fuel	Diesel	Open / Enclosure	Open
Sizing Methodology	Conventional		
Capacity Used	33.5%		
Engine			
Make/Model	3516	Emissions / Certifications	LOW BSFC
Aspiration	TA	Governor	WOODWARD
Cylinder Configuration	VEE - 16	Aftercooler Type	JWAC
Speed	1500 RPM	Displacement	4,211 Cubic Inch / 69 Liter

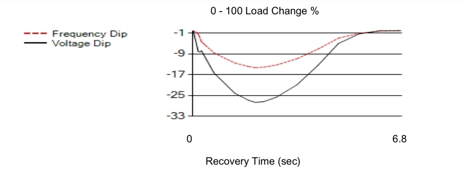
Engine Performance Number	DM7962	Bore	170
Fuel Consumption at 100% Load	101.1 gph	Stroke	190
Alternator			
Alternator Type/Frame Size	SR5 / 1844	Insulation Class	H
Alternator Winding Pitch	0.6667	Temperature Rise	80 C
Excitation/Winding Type	PM / FORM	Number Of Poles	4
Alternator Arrangement Number	3723056	Number of Leads	6
Subtransient Reactance X"d	0.0844	Rated Amps	2,634.2

**** See your Caterpillar dealer and/or Spec Sheet for technical information.

***** Package Power Tolerance: +/- 5%

Block Load(Only) Transient Response *

Load Change %	FDip %	VDip %	Recovery Time (sec)
0 - 25	2.2	3.6	< 3
0 - 50	4.4	8.0	< 3
0 - 75	7.9	15.0	3.6
0 - 100	14.2	27.7	6.8



Transient Performance

Block Load (only) Transient Response values are at factory conditions with a resistive load. This information is representative of a typical Cat generator set, but is not guaranteed. Generator set block load capabilities at site conditions may vary from factory transient response test results due to site altitude, site ambient, and engine to engine variation.

CAT

Load Report

Project Name	WPP with 18 WTGs 1step	Electricity Supply	50 Hz 400/230 V
Customer Name		Rating Type	Prime
Region	EAME/CIS	Max. Ambient Temperature	77.0 F
Prepared By	Vigan Spahiu	Altitude	500.0 Ft. A.S.L
Modified Date	6-May-2020	Humidity	30%
Generator Set Model	(1) of 3516	Nameplate Rating	1,460.0 ekW / 1,825.0 kVA / 0.8 PF

Load Details		Permitted		Predicted		Transient Inrush		Running		Resultant Peak		Cumulative Running	
Load Step	Load Description	FDip	VDip	FDip	VDip	SkVA	SkW	kVA	kW	SkVA	SkW	kVA	kW
Step 1-Voltage dip restriction													
1.1	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
1.2	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
1.3	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
	Step 1 Total	5%	15%	3.0%	14.4%	2,538.7	507.7	607.5	486.0				
	Total Through Step 1									2,538.7	507.7	607.5	486.0
Load Analysis Summary													
						Maximum Step				Maximum Peak		Final Running	
						SkVA	SkW			SkVA	SkW	kVA	kW
						2,538.7	507.7			2,538.7	507.7	607.5	486.0

Audit Rule(s)

Warning: The running load connected to the selected genset(s) is low compared to its site rating. Long term operation of diesel engines at light load can cause problems that may result in excessive oil consumption and reduced life to overhaul. It is recommended that you consult with your Caterpillar dealer for application advice.

A.2 Sequential starting case 2

Case 2 represents starting of the yaw motors for the 18 WTGs in two steps. First step the yaw motors for the 12 WTGs will simultaneously start and second step the remaining yaw motors in the 6 WTGs will start while supplying the required running power for already energized yaw motors in the first step.

Project Sizing Report

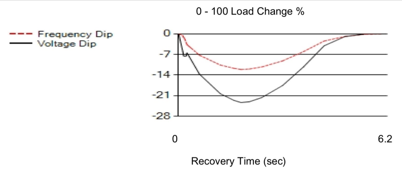
Project Name	WPP with 18 WTGs 2steps	Electricity Supply	50 Hz 400/230 V
Customer Name		Connection	STAR
Region	EAME/CIS	Max. Ambient Temperature	77.0 F
Prepared By	Vigan Spahiu	Altitude	500.0 Ft. A.S.L
Modified Date	6-May-2020	Humidity	30%
Load Analysis Summary			
Max Transient Load Step	1,692.5 SkVA / 338.5 SkW		
Peak Transient Load Step	1,692.5 SkVA / 493.2 SkW		
Final Running Load	607.5 kVA / 486.0 kW / 0.80 PF		
Max Running Non Linear Load	0.0 RkVA		
Maximum Running Load	607.5 kVA / 486.0 kW		
Selection Criteria	Step 1 Voltage dip restriction		
Generator Set			
Generator Set Model	(1) of 3512	Nameplate Rating	920.0 ekW / 1,150.0 kVA / 0.8 PF
Voltage Regulator and Slope	CDVR 2:1 slope;	Site Output Rating	920 ekW / 1,150 kVA
Feature Code	512DRA7	Rating Type	Prime
Fuel	Diesel	Open / Enclosure	Open
Sizing Methodology	Conventional		
Capacity Used	52.8%		
Engine			
Make/Model	3512	Emissions / Certifications	LOW BSFC
Aspiration	TA	Governor	WOODWARD
Cylinder Configuration	VEE - 12	Aftercooler Type	JWAC
Speed	1500 RPM	Displacement	3,158 Cubic Inch / 52 Liter
Engine Performance Number	DM8219	Bore	170
Fuel Consumption at 100% Load	63.9 gph	Stroke	190
Alternator			
Alternator Type/Frame Size	SR5 / 1488	Insulation Class	H
Alternator Winding Pitch	0.6667	Temperature Rise	80 C
Excitation/Winding Type	PM / FORM	Number Of Poles	4
Alternator Arrangement Number	2523928	Number of Leads	6
Subtransient Reactance X"d	0.0863	Rated Amps	1,659.9

**** See your Caterpillar dealer and/or Spec Sheet for technical information.

***** Package Power Tolerance: +/- 5%

Block Load(Only) Transient Response *

Load Change %	FDip %	VDip %	Recovery Time (sec)
0 - 25	2.0	3.1	< 3
0 - 50	3.9	7.1	< 3
0 - 75	7.1	13.3	< 3
0 - 100	12.1	23.3	6.2



Transient Performance

Block Load (only) Transient Response values are at factory conditions with a resistive load. This information is representative of a typical Cat generator set, but is not guaranteed. Generator set block load capabilities at site conditions may vary from factory transient response test results due to site altitude, site ambient, and engine to engine variation.

Load Report

Project Name	WPP with 18 WTGs 2steps	Electricity Supply	50 Hz 400/230 V
Customer Name		Rating Type	Prime
Region	EAME/CIS	Max. Ambient Temperature	77.0 F
Prepared By	Vigan Spahiu	Altitude	500.0 Ft. A.S.L
Modified Date	6-May-2020	Humidity	30%
Generator Set Model	(1) of 3512	Nameplate Rating	920.0 ekW / 1,150.0 kVA / 0.8 PF

Load Details		Permitted		Predicted		Transient Inrush		Running		Resultant Peak		Cumulative Running	
Load Step	Load Description	FDip	VDip	FDip	VDip	SkVA	SkW	kVA	kW	SkVA	SkW	kVA	kW
Step 1-Voltage dip restriction													
1.1	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
1.2	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
	Step 1 Total	5%	15%	2.8%	14.5%	1,692.5	338.5	405.0	324.0				
	Total Through Step 1									1,692.5	338.5	405.0	324.0
Step 2-Step Passed													
2.1	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
	Step 2 Total	5%	15%	1.4%	7.8%	846.2	169.2	202.5	162.0				
	Total Through Step 2									1,180.2	493.2	607.5	486.0
Load Analysis Summary													
						Maximum Step				Maximum Peak		Final Running	
						SkVA	SkW			SkVA	SkW	kVA	kW
						1,692.5	338.5			1,692.5	493.2	607.5	486.0

A.3 Sequential starting case 3

Case 3 is divided in three steps where each step will start motors at one feeder at a time and supply steady power to the already started motors in the previous feeder.

Project Sizing Report

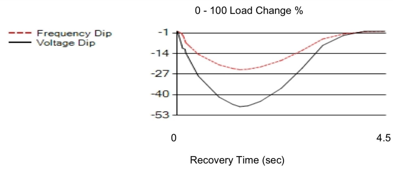
Project Name	WPP with 18 WTGs 3steps	Electricity Supply	50 Hz 400/230 V
Customer Name		Connection	STAR
Region	EAME/CIS	Max. Ambient Temperature	77.0 F
Prepared By	Vigan Spahiu	Altitude	500.0 Ft. A.S.L
Modified Date	6-May-2020	Humidity	30%
Load Analysis Summary			
Max Transient Load Step	846.2 SkVA / 169.2 SkW		
Peak Transient Load Step	1,180.2 SkVA / 493.2 SkW		
Final Running Load	607.5 kVA / 486.0 kW / 0.80 PF		
Max Running Non Linear Load	0.0 RkVA		
Maximum Running Load	607.5 kVA / 486.0 kW		
Selection Criteria	Step 1 Voltage dip restriction		
Generator Set			
Generator Set Model	(1) of C18	Nameplate Rating	616.0 ekW / 770.0 kVA / 0.8 PF
Voltage Regulator and Slope	IVR 2:1 slope;	Site Output Rating	614.6 ekW / 768.2 kVA
Feature Code	C18DEIE	Rating Type	Prime
Fuel	Diesel	Open / Enclosure	Open
Sizing Methodology	Conventional		
Capacity Used	79.1%		
Engine			
Make/Model	C18	Emissions / Certifications	LOW BSFC
Aspiration	TA	Governor	ELEC
Cylinder Configuration	INLINE - 6	Aftercooler Type	ATAAC
Speed	1500 RPM	Displacement	1,106 Cubic Inch / 18 Liter
Engine Performance Number	EM3831	Bore	145
Fuel Consumption at 100% Load	42.7 gph	Stroke	183
Alternator			
Alternator Type/Frame Size	LC / LC7224L	Insulation Class	H
Alternator Winding Pitch	0.6667	Temperature Rise	125 C
Excitation/Winding Type	AREP / RANDOM	Number Of Poles	4
Alternator Arrangement Number	5618489	Number of Leads	6
Subtransient Reactance X"d	0.1251	Rated Amps	1,111.4

**** See your Caterpillar dealer and/or Spec Sheet for technical information.

***** Package Power Tolerance: +/- 5%

Block Load(Only) Transient Response *

Load Change %	FDip %	VDip %	Recovery Time (sec)
0 - 25	3.3	5.9	< 3
0 - 50	9.1	17.4	< 3
0 - 75	16.7	32.6	3.3
0 - 100	24.2	47.6	4.5



Transient Performance

Block Load (only) Transient Response values are at factory conditions with a resistive load. This information is representative of a typical Cat generator set, but is not guaranteed. Generator set block load capabilities at site conditions may vary from factory transient response test results due to site altitude, site ambient, and engine to engine variation.

Load Report

Project Name	WPP with 18 WTGs 3steps	Electricity Supply	50 Hz 400/230 V
Customer Name		Rating Type	Prime
Region	EAME/CIS	Max. Ambient Temperature	77.0 F
Prepared By	Vigan Spahiu	Altitude	500.0 Ft. A.S.L
Modified Date	6-May-2020	Humidity	30%
Generator Set Model	(1) of C18	Nameplate Rating	616.0 ekW / 770.0 kVA / 0.8 PF

Load Details		Permitted		Predicted		Transient Inrush		Running		Resultant Peak		Cumulative Running	
Load Step	Load Description	FDip	VDip	FDip	VDip	SkVA	SkW	kVA	kW	SkVA	SkW	kVA	kW
Step 1-Voltage dip restriction													
1.1	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
	Step 1 Total	5%	15%	3.8%	14.6%	846.2	169.2	202.5	162.0				
	Total Through Step 1									846.2	169.2	202.5	162.0
Step 2-Voltage dip restriction													
2.1	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
	Step 2 Total	5%	15%	3.8%	14.6%	846.2	169.2	202.5	162.0				
	Total Through Step 2									1,006.7	331.2	405.0	324.0
Step 3-Voltage dip restriction													
3.1	48x2.70 kW - Three Phase Motor5,15: IEC, 3-Phase Motor, Direct On Line, Loaded, Single	5%	15%			846.2	169.2	202.5	162.0				
	Step 3 Total	5%	15%	3.8%	14.6%	846.2	169.2	202.5	162.0				
	Total Through Step 3									1,180.2	493.2	607.5	486.0
Load Analysis Summary													
						Maximum Step				Maximum Peak		Final Running	
						SkVA	SkW			SkVA	SkW	kVA	kW
						846.2	169.2			1,180.2	493.2	607.5	486.0