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POWER SYSTEM WITH VARIABLE SPEED WIND TURBINE AND DIESEL GENERATION UNITS

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ABSTRACT

This paper presents a power system consisting of wind turbines, diesel generation units, and energy storage system. Both wind turbines and diesel engine adopt variable speed operation mode;and power electronic interface are used for the generation units which provide flexible and wide range of control on the power. The system configuration, characteristics, operation principles are presented. The controller and control strategies are discussed. The simulation studies have been performed and the results are presented.

Keywords: Dispersed Generation; Diesel Generation Unit; Wind Power; Energy Storage; Power Electronic Interface

I. INTRODUCTION

At present, a common way to supply electricity to remote loads is to use a diesel engine-generator set. However, diesel fuel, like other conventional energy sources, such as oil, natural gas, coal and nuclear, is finite and generates pollution. Clean renewable energy sources for example, solar, wind and wave, are abundant energy source globally, and have obvious advantages of benefiting the environment, therefore, the use of renewable sources is actively promoted to meet environmental goals and to provide long-term energy security. In recent years, the developments of renewable energy have attracted significant attentions, and have been advanced rapidly, in particular, wind energy is the most competitive renewable energy sourced electricity generation approach and the globally installed wind power generation capacity is increased quickly.

While wind turbines have been integrated into power systems in large scale, they may also be conveniently used in autonomous systems. However, the availability of renewable energy sources has strong daily and seasonal patterns. For a wind turbine, no output power guarantee can be given, because days with wind speed lower than the cut in speed of the wind turbine may occur, resulting in no power generation. Therefore, hybrid power systems, such as wind turbines, diesel units, and/or energy storage devices, could be a choice of the electricity supply for remote locations.

The capability of power electronic as the interface is almost essential for many new power generation systems. The variable speed operation enabled by power electronic system can reduce mechanical stress and smooth the fluctuation of the power injected into the grid, which results in less wear and tear on the tower, gearbox and other components in the drive train of the wind turbine. Also variable speed systems can increase the production of the energy and reduce noise. Furthermore, power electronic in a diesel generation system could remove the speed limit on the engine, combined with battery energy storage; making the system more efficient.

This paper describes a hybrid generation system consisting of a wind turbine, a diesel unit and an energy storage system. The system configuration and power electronic interfaces are presented. The characteristics of the generation units are discussed. The operation and control principles of the different generation units in an autonomous power system are developed. In particularly, a fuzzy controller is developed for the diesel engine speed controller. The simulation models are established and simulation studies have been performed under various conditions. The results show that the system can provide reliable and good quality power to the customers in autonomous power systems.

II. SYSTEM CONFIGURATION

A schematic configuration of the studied hybrid generation system is shown in Fig. 1, where the wind turbine, diesel generation unit, energy storage system and power system load are connected in parallel to form a simple power system.

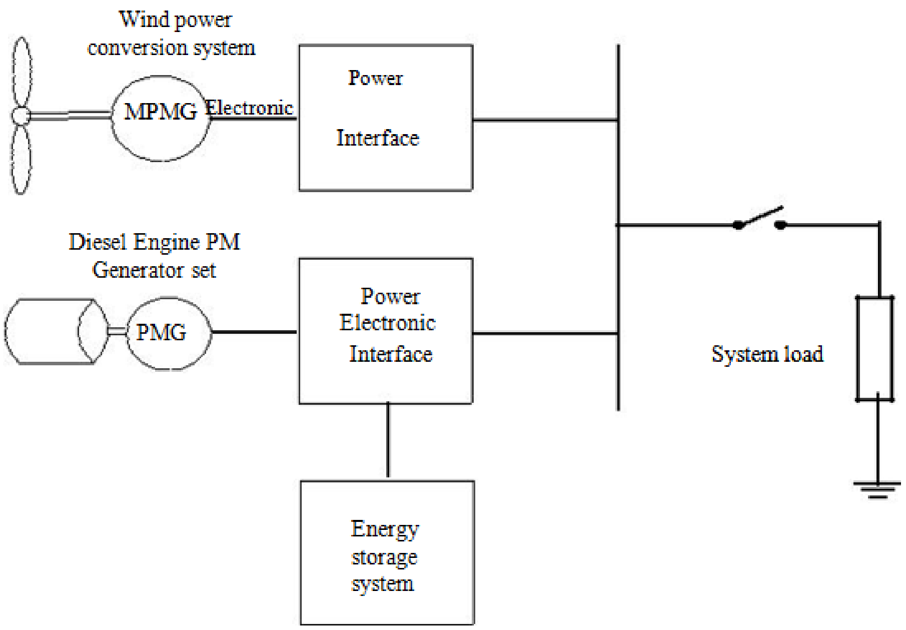


Fig. 1 Schematics of the Studied Autonomous Power System

The wind power conversion system consists of a wind turbine, a generator and the associated power electronic converters. Various types of generators can be used for variable speed wind power conversion systems; and the modular permanent magnet generator (MPMG) [Spooner et al. (1996)] is taken in this study. Several types of power electronic conversion systems for the MPMG have been studied [Chen et al. (1998)], one of the reported interfaces [Chen et al. (2001)]is used for this study as shown schematically in Fig. 2.The power electronic interface includes the modular single phase diode rectifiers [Chen et al. (1998)]shown in Fig. 3, a boost type of dc/dc converter and a voltage source converter (VSC) as illustrated in Fig. 2.The dc/dc converter keeps a required dc voltage at the dc input of the VSC which injects power into the ac system at a constant frequency.

In a diesel generation system, the generation unit uses a normal permanent magnet (PM) generator, which does not have an excitation control system, so that the requirement on the maintenance is reduced, but the terminal voltage cannot be controlled like a field excited synchronous generator. Furthermore, if a synchronous generator is used, the generator may be directly connected to the ac load, then the governor of the diesel engine needs to keep the speed constant due to the restriction of the operation frequency of the load. However, a diesel engine would have high rate of consumption at a constant speed with a light load, a minimum load about 40% of the rated capacity is often recommended by the manufacturers. Hence, a power electronic interfaced variable speed system is considered.

The power electronic interface decouples the frequency of the generator and the connected load, so that the speed of the generator can be varied to reduce the fuel consumption and emission level. Additionally, the frequency decouple enables a normal permanent magnet (PM) generator to be used instead of a field excited synchronous generator, while voltage controllability is still held.

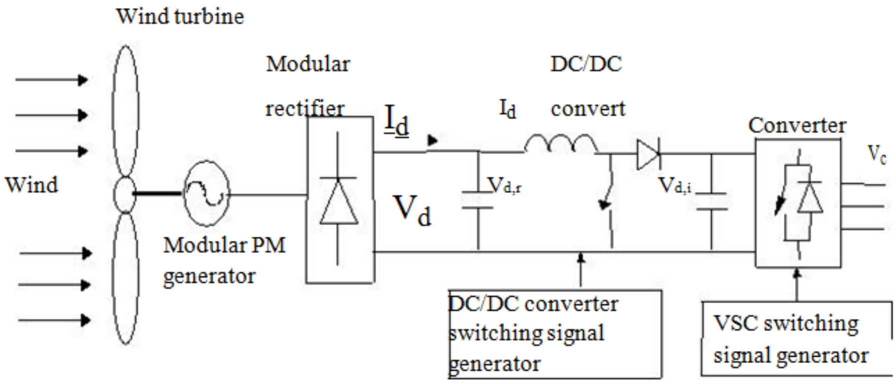


Fig. 2 Schematics of the Wind Power Conversion System

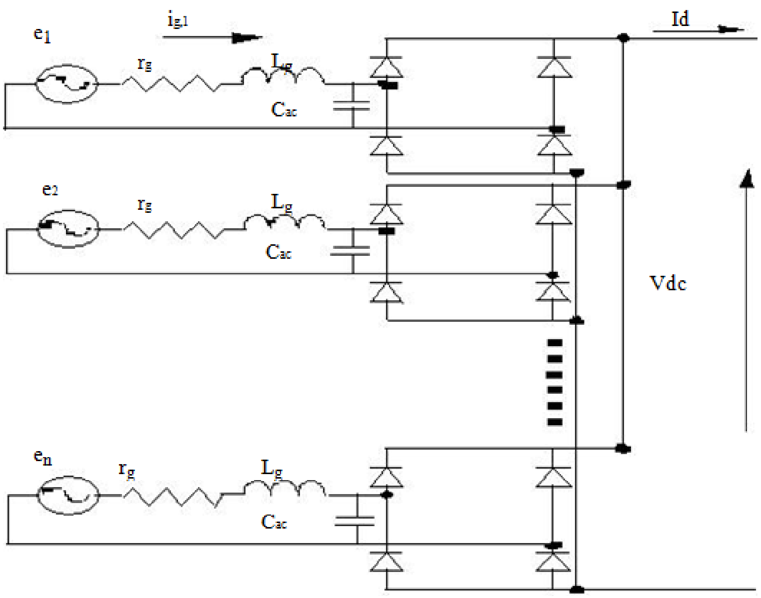


Fig. 3 Modular Connection of Stator Coil and Rectifier

The power electronic system interface for the diesel engine adopts an ac/dc/ac configuration as illustrated in Fig. 4.

The ac/dc conversion is performed by a normal three phase diode rectifier, which is low cost and reliable, and has very little maintenance requirement. Due to the variation of the engine speed, the dc voltage at the rectifier dc terminal is varying. In the dc part of the system, a chopper type of dc/dc converter is used to regulate the voltage at the dc terminal of the dc/ac converter and to keep the voltage at the reference level for the dc/ac converter and the energy storage batteries. The inverter converts the dc voltage into ac voltage with desired magnitude and frequency.

The energy storage devices are used in the hybrid generating system to level out the erratic differences between the generation and load consumption. The energy storage devices can effetively provide power to meet sudden load increments. As shown in Fig. 4, the energy storage device is connected to the regulated dc link with a bi-directional dc/dc converter which controls the direction and flow of the power of the energy storage device, i.e. its charge/discharge.

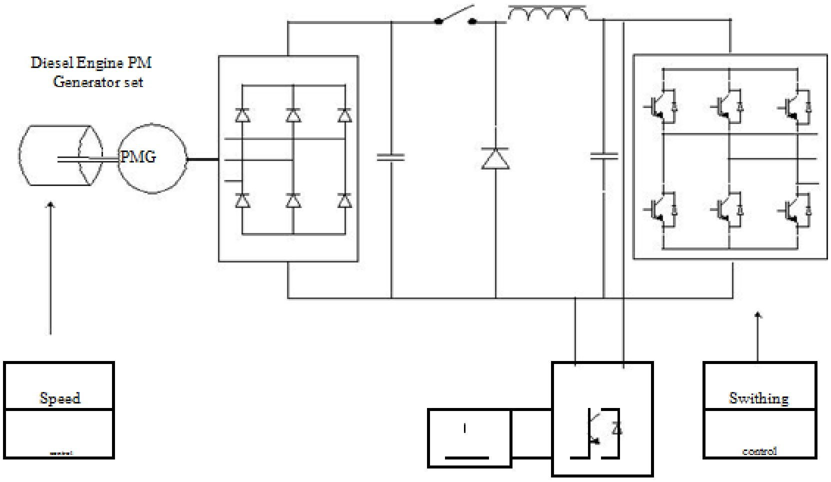


Fig. 4 Schematics of Variable Speed Diesel-pm Generator System

Therefore, the power electronic interfaces have a function of de-couplelling and provide a desired voltage with a fixed frequency. Also the fast controllable power electronic converter can play an important role in the control of the system dynamics and power quality.

In the generation system, the wind power converter is operated to maximize the wind energy capture, the captured energy is supplied to the load directly, and the energy storage device keeps the suplus power generated. The battery can provide a quick support for a short period. If the unbalance becomes significant, for example in a period of quite wind, the diesel generation unit will be put into operation to cover the power insufficiency.

III. CHARACTERISTICS OF GENERATION SYSTEMS

3.1 Wind Power Conversion System

The aerodynamic power of a wind turbine is given by:

1 2 3 (1)

ρ density, *R*is the turbine radius, *v*is

Where is the air = 2

the wind speed, and *CP*is the turbine power coefficient which represents the power conversion efficiency of a turbine.*CP* is a function of the tip speed ratio (λ), as well as the blade pitch angle (β) in a pitch controlled wind turbine. In the case of grid connection, β may be considered as a constant for the optimal power capture with the wind speed lower than the rated speed, then it is adjusted to regulate the power output. $\lambda$is defined as the ratio of

the tip speed of the turbine
blades to wind speed, and given by:

$$= \underline{\cdot\Omega}$$

A typical *CP*-*λ*curve is shown in Fig. 5. It can be seen that there is a maximum power coefficient, *CP*,max. Normally, a variable speed wind turbine follows the *CP*,max to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at *λ*opt, then operates within the rated power during the high wind by the active control of the blade pitch angle or the passive regulation based on aerodynamic stall. A typical power-wind speed curve is shown in Fig. 6.

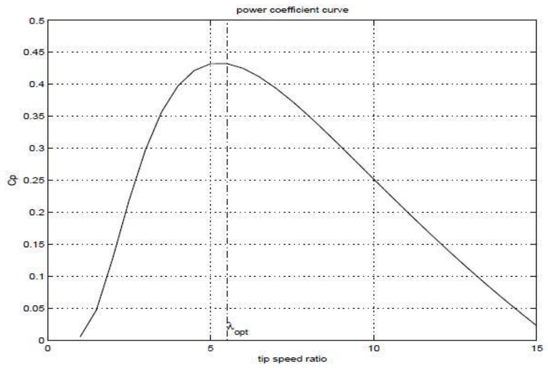


Fig. 5 Typical cp-λ Curve

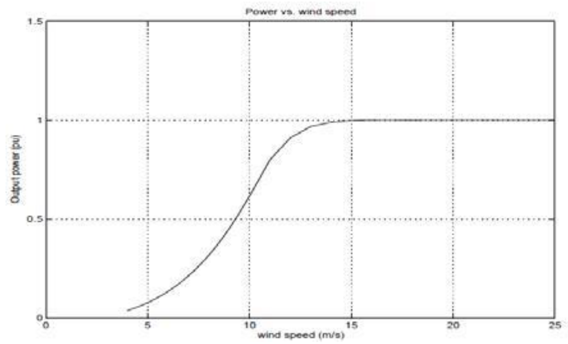


Fig 6 Power-Wind Speed Characteristics

In the range of maximum power capture, a nearly fixed ratio of the tip speed of the turbine blades to wind speed is kept. The modular wind turbine generator operates at a variable speed and produces a variable voltage. A capacitor connection at the rectifier ac terminal can modify the characteristics of the wind generator, therefore, the optimal power is delivered into the dc side. The typical power and voltage characteristics at the dc terminal of the diode rectifiers are shown in Fig. 7. In order to convert the varying dc voltage into a constant voltage, a boost converter is used as shown in Fig. 2.

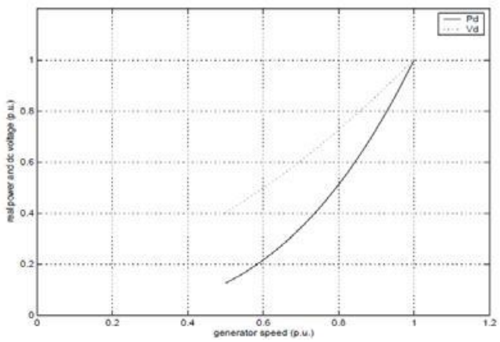


Fig. 7 Wind Power Generator-Rectifier Characteristics (Power And Voltage In Variable Speed Zone)

However, in an autonomous system, the ability of pitch control may be used for power regulation to meet the load demand, i.e. limiting the wind power input by adjusting pitch angle so that the production and consumption may be balanced.

3.2 Diesel Generation Unit

The performance of a diesel engine may be affected by many non-linear factors. The diesel generation unit can be controlled to follow a set of the desired reference characteristic curves [Grzesiak et al. (1998)] as shown in Fig. 8. The voltage generated by the permanent magnet generator presents a linear characteristic related to the engine speed. The variable voltage is then converted by an ac/dc/ac power electronic interface, which consists of mainly a diode rectifier, a dc/dc converter and a voltage source converter (VSC). The dc-dc conversion system keeps the voltage at the dc terminal of the inverter within the desired range. The main function of the VSC is to produce three-phase ac voltage; and a fixed amplitude modulation ratio may be used for the converter if the converter input dc voltage is controlled to the required voltage level.

IV. POWER ELECTRONICS AND THEIR CONTROL SYSTEM CONFIGURATION

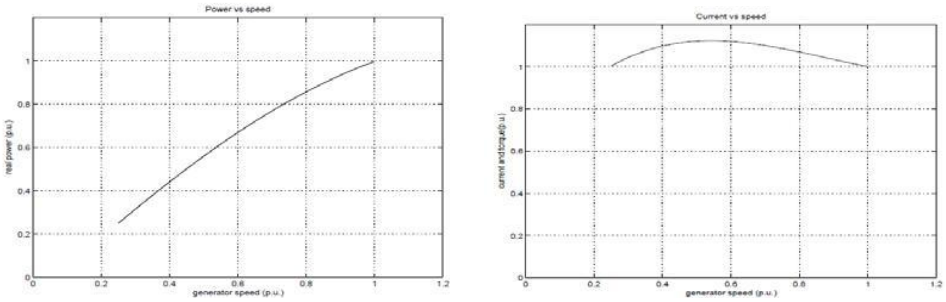
The power electronic converters and their control play a very important role in the power system. In this section, the operation and control of the power electronic converters are presented.

4.1 DC/DC Converters

Three DC/DC converters are used in the system for the wind turbine, diesel generator and energy storage system respectively.

1) DC/DC Converter for the Wind Power Generator

The variable speed wind generator produces a voltage which is varying in both the magnitude and frequency; the multi -pulse diode rectifier system is used to deliver a smooth dc voltage [Chen et al. (2001)].Then a dc/dc boost shown in Fig. 9 is used to convert the voltage into a relative constant and higher dc voltage at the voltage source converter (VSC) input terminal. The dc/dc converter divides the dc link into two levels. In order to optimize the wind energy capture, a variable dc voltage at the diode rectifier terminal is required to follow the operation characteristic shown in Fig. 7.



(a) Characteristic of power and speed. (b) Characteristic of current and speed.

Fig. 8 Diesel Engine Operational Characteristics

A curve of switching duty ratio of the boost is illustrated in Fig. 10 in variable speed operation for the maximum power. However, the wind turbine in the studied system may be required to limit the power output to match the load demand. Therefore, the dc/dc converter control has to be related to the power control and coordinated with the pitch angle control. The block diagram of the controller for the dc/dc converter is sketched in Fig. 11.

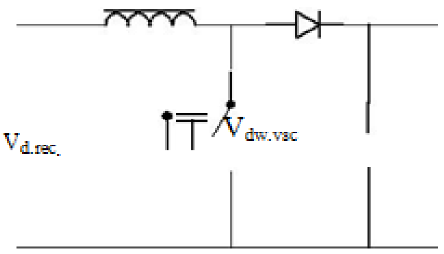


Fig. 9 Non-Isolated Boost Dc/Dc Converter for Wind Turbine

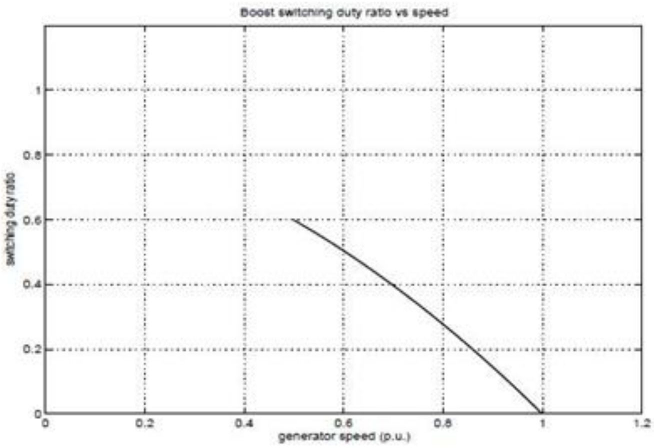


Fig. 10 Switching Duty Ratio of Boost in Wind Power Generation (Maximum Power Capture)

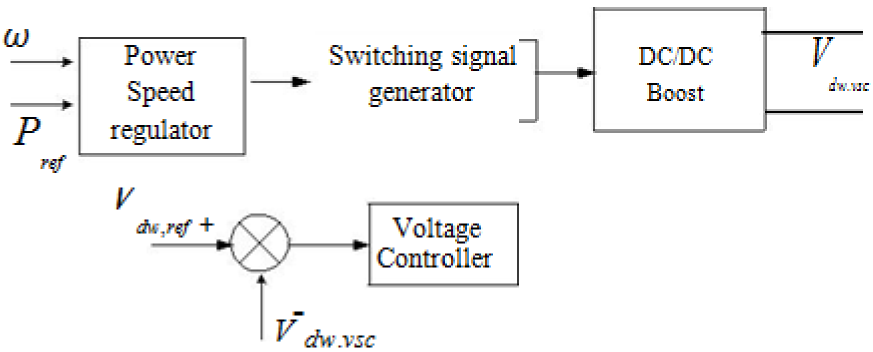


Fig. 11control System for the Boost in Wind Turbine System

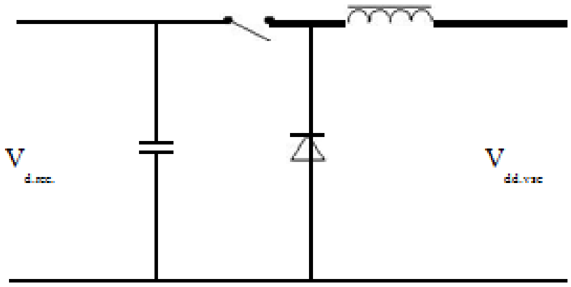


Fig. 12 Non-Isolated Buck Dc/Dc Converter in Diesel Generation Unit

2) DC/DC Chopper for the Diesel Engine Rectifier

Similar to the variable speed wind power generator, the variable speed permanent magnet generator, driven by the diesel engine, produces a voltage in proportion to the machine speed. A normal three-phase diode rectifier system is used to convert the variable frequency ac voltage into a dc voltage. Due to the variation of the engine speed, the dc voltage at the rectifier output is varying. In order to satisfy the requirements of the constant voltage load, adc/dc converter shown in Fig. 12 is used to produce an almost constant dc voltage for the connected inverter and the energy storage batteries.

The dc/dc converter needs to keep the output dc voltage at a specified constant value, while the input dc voltage is varying with the machine speed which is further specified by the power-speed characteristics. Therefore, the duty ratio of the chopper would be a function of the speed of the diesel engine as shown in Fig. 13.

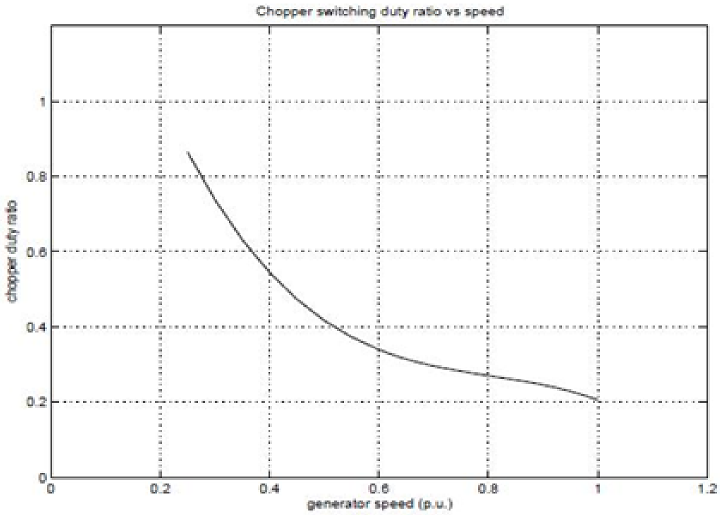


Fig. 13 Switching Duty Ratio of Chopper in the Diesel Engine System

A controller for the chopper is illustrated in Fig. 14. The input to the switching signal generator consists of two components, one is from the PI controller output, and the other is set on the basis of the relationship between the reference power (speed) and duty ratio (the voltage) shown in Fig. 13. The PI controller generates a correction component for the switching signal generator to hold the dc voltage at the desired reference levelunder a varying input dc voltage condition.

3) DC/DC Converter for Energy Storage System

Differing from the above two dc/dc converter systems, the dc/dc converter for the energy storage system has to be able to deliver the power in both directions, to charge and discharge the batteries as necessary. The discharge procedure should be controlled to hold the dc voltage of the system and support the system power balance, while the charge procedure may be controlled to achieve a long life time of the energy storage batteries.

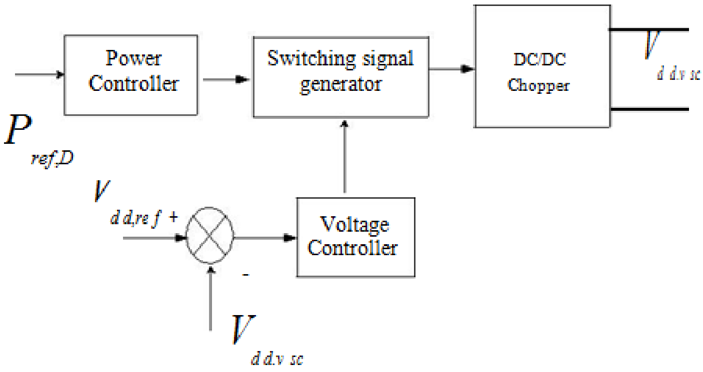


Fig. 14 Switching Duty Ratio Of Chopper In The Diesel Engine System

The circuit configurations and control strategies of bi-directional dc/dc converters have been discussed in literature [Hunter et al. (1994)]. This paper will not discuss the details of bi-directional dc/dc converters.

4.2 DC/AC Converters

The two dc/ac converters in the system are used respectively for the wind power conversion system and the diesel generation unit with the energy storage system. The functions of these converters are to deliver the active and reactive power to the consumer with the required voltage magnitude and frequency. The voltage source converters (VSC) can be a simple two level converter as shown in Fig. 15 though complex converter topologies, such as multi-level converters or multi-module converters, may be used depending on the required power level. The two VSCs may have different control strategies; and the VSC for the wind power conversion system may only be required to transfer active power in one direction, i.e. from the wind turbine to the consumer; however, the VSC used for the diesel generation unit with the energy storage system may need to transfer power in both directions.

As usual, PWM switching strategies can be used for both dc/ac voltage source converters; and ac filters are connected at the ac terminals of the converters to limit the harmonic generated by switching the semiconductors.

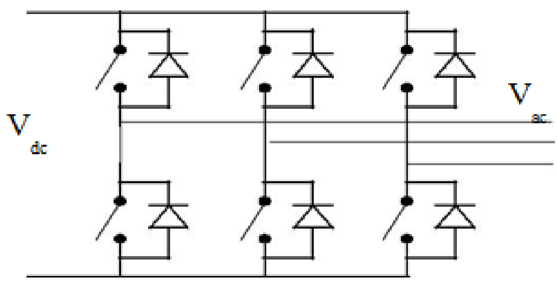


Fig. 15 DC/AC Inverter for Generation System Interface

The main function of the VSC is to produce a three-phase ac voltage; and a vector control strategy may be used for the VSC.

One VSC can work to hold the system voltage and frequency. The other VSC works as a power source to inject the specified active power and reactive power into the system, a block vector control system diagram of such a power injection converter is shown in Fig. 16, the control system controls the converter to deliver appropriate d and q axis currents into the system so as to deliver the specified power into the system.

V. POWER CONTROL SYSTEM OF GENERATION UNIT

The power supply units of the system are the wind turbine, diesel engine and energy storage. The objective of the power control is to control the varying power generations to meet energy demand of the consumer; the energy storage device is used to provide short term coverage of the power demand, especially the rapid load variation to ensure the voltage, power quality and stability of the system. Here the controls of wind power generator and diesel generation unit are discussed.

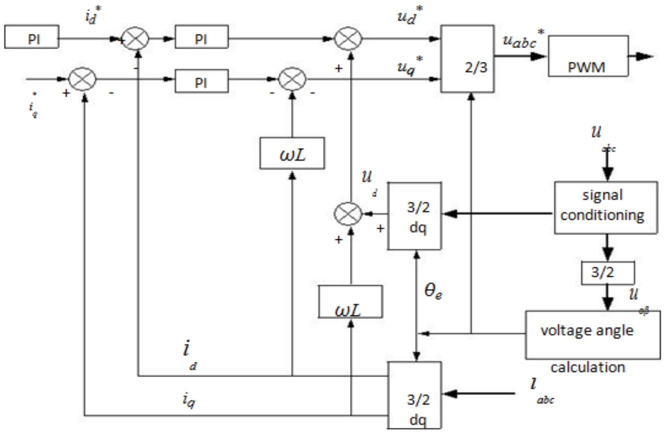


Fig. 16 Control of Vsc System For Power Injection

5.1 Wind Turbine Power Control

The available power that may be provided by the wind turbine depends on the wind speed, and therefore, varying with the wind speed. The variable speed wind turbine can operate at an optimal tip-speed ratio for the optimal power capture until the machine reaches the rated condition then the input power will be limited by a pitch control system. The pitch controller of the wind turbine is illustrated in Fig. 17. Similar to a grid connected system, the pitch control system will regulate the wind power input to the system and limit the power when wind speed is too high.

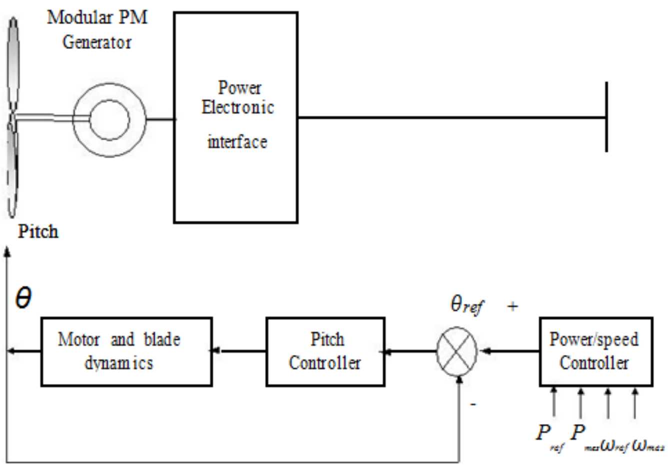


Fig. 17 Block Diagram of Pitch Control of the Wind Turbine

The output power of a wind turbine can not exceed the available wind power, but it may be reduced by a pitch control so as to balance the system load if the power generated from the wind turbine cannot be absorbed by the load and energy storage system. A schematic of such a control system is illustrated in Fig. 17.

5.2 Speed Control of Diesel Generation Unit

The control system of diesel unit consists of the speed controller and the power electronic controller. The speed controller adjusts the fuel input to meet the demands of the system power balance under the variations of wind power generation and system load. While the control system for the power electronic system controls the dc/dc converter to provide the voltage source converter with an almost constant dc voltage input and it also controls the converter to produce a three-phase voltage output with desired voltage amplitude and frequency. Furthermore, the power electronic control system is coordinated with the speed control system to minimize the transient disturbance.

Diesel engine system is a non-linear system, there are many factors would affect its operation [Grzesiak et al. (1998), Haddad et al. (1984)]. Considering the non-ideal features of the system, such as non-linearity and power loss, speed control system based on fuzzy logic features more effective and robustic. The block diagram of the diesel generation system is shown in Fig. 18.In the diesel system, the power generation relies on the fuel input. The principal task of the speed controller is to control the fuel input, therefore the output of the controller is the control signal to the actuator.

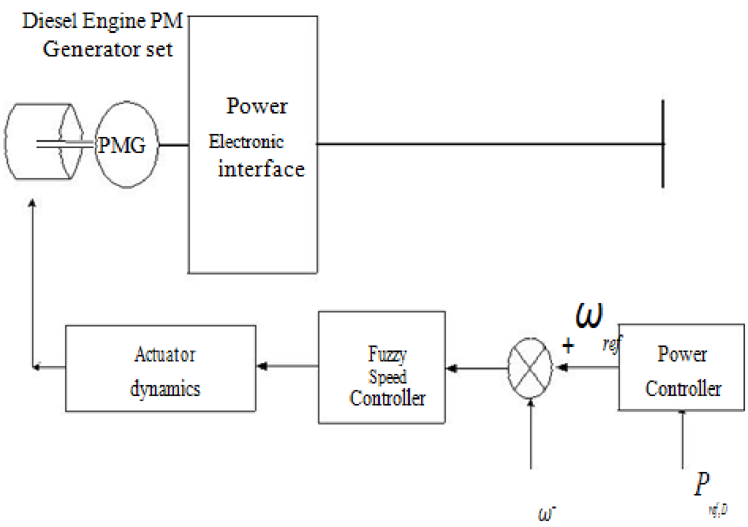


Fig. 18 Block Diagram of Speed Control of the Diesel Engine

Fuzzy logic method has some obvious advantages such as tolerant to imprecise data, can deal flexibly with non-linear system since an accurate mathematical model is not required. These advantages have made fuzzy logic become very useful in control techniques in recent years, especially when the controlled system is difficult to be modeled using formulas.

Diesel engine system is a non-linear system. In a diesel engine system, there are many factors would affect its operation [Grzesiak et al. (1998), Haddad et al. (1984)]. Due to so many factors affecting the operation of the diesel engine, a fuzzy logic control method is more effective.

The fuzzy logic control unit is shown in Fig. 19. The inputs of the fuzzy logic controller are based on a general scheme using error and change rate of the error, where the speed error and its derivative are evaluated and fuzzified. The fuzzified signals are then sent to the inference block. Finally, the control signal is obtained with a defuzzification operation. Such control decisions are not the consequence of a single valued generation system speed measurement but, instead, the consequence of speed error with respect to the speed reference, which is correspondent to the engine loading level variation, and the change rate of the speed error.

The input and output parameters of the fuzzy logic controller are linguistic variables, that are modeled by fuzzy sets. The number of fuzzy sets for each fuzzy variable varies according to the application.

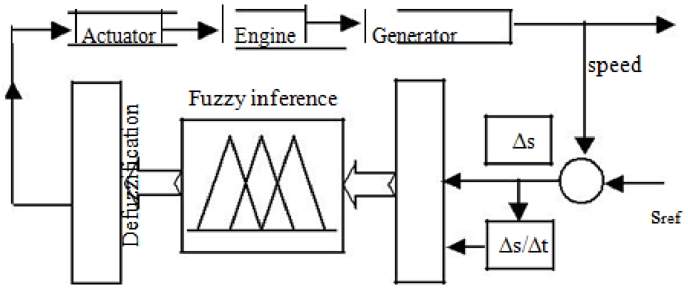


Fig. 19 Block Diagram of the Engine Speed Controller with A Fuzzy Logic Core

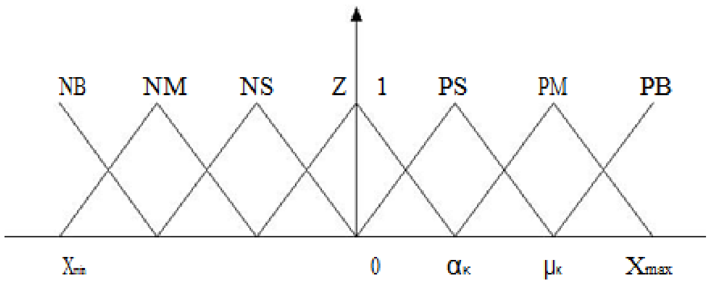


Fig. 20 Seven Triangular Membership Functions

Membership functions represent a number of quantized overlapping fuzzy sets (linguistic variables) for each of the input signals to the fuzzy logic controller and output signals from it. The membership functions assigned to each fuzzy set map the crisp values into fuzzy values. Various shapes of membership functions can be found in fuzzy logic applications**,** in this study, the triangular shape is adopted as shown in Fig. 20. The output is used as fuel control signal.

5.3 Control of Energy Storage Device

The energy storage device is connected to the dc terminal of the VSC for the diesel unit through a dc/dc converter. Both the VSC and dc/dc converter of energy storage device are bi-directional, which enables the energy storage device to release the stored energy to compensate short term energy unbalance or take energy from either the wind turbine or the diesel unit.

Various type energy storage devices may be used. In this study, the lead acid battery is assumed. The lead acid battery is available in a wide range of sizes and capacities. It has the advantage of being relatively inexpensive in terms of its energy storage capacity per unit cost [Hunter et al. (1994)]. The control of the bi-directional dc/dc converter should consider the influence of charging current so as to control the charging current to achieve a prolonged battery life.

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The control systems for the diesel generation unit with energy storage are illustrated in Fig. 21. The complete control system of the diesel generation/energy storage unit consists of the diesel engine variable speed controller and the controller for the power electronic converters. The variable speed controller adjusts the fuel input for the requirement of balancing the system power under the variations of wind power generation and system load;and it is coordinated with the power electronic control system to minimize the transient disturbance.

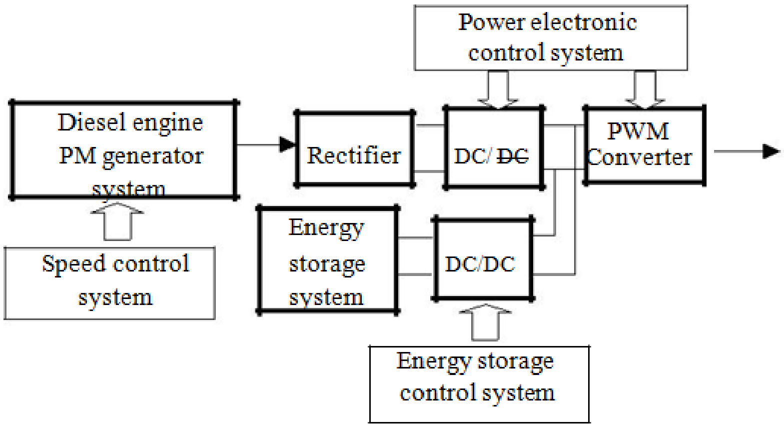

Fig. 21 Block Diagram of A Diesel Generation Unit with Control Systems

VI. OPERATION MODES

The main task of operating an autonomous power system is to keep the power balance with good power quality. Moreover, in the discussed system, as much as possible wind energy may be utilized, so that the fossil fuel emission can be minimized. The operation strategy for the studied power system needs to control the wind turbine, the diesel generation unit and the energy storage unit respectively, and also perform the coordination among these power supply units. Depending on the level of the power system load, various operation modes may exist as listed in Table 1.

Table 1 Operation Modes

	Wind turbine	Energy storage	Diesel unit
Mode 1	operation		
Mode 2	operation	charging	
Mode 3	operation	discharging	
Mode 4	operation	charging	operation
Mode 5	operation		operation
Mode 6		charging	operation
Mode 7			operation

If the consumers' power demand is higher than that the wind turbine can supply, typically in the case of a light wind condition, the energy storage or the diesel engine may be put into operation to provide the required power. Whether the diesel engine is put into operation depends on the shortage of the power supply and the charge of state (SOC) of the energy storage system.

VII. SIMULATION STUDY

The models of the above systems have been developed in PSCAD/EMTDC. The simulation studies have been performed with a simplified system shown in Fig. 22, wheretwo equivalent loads are connected.

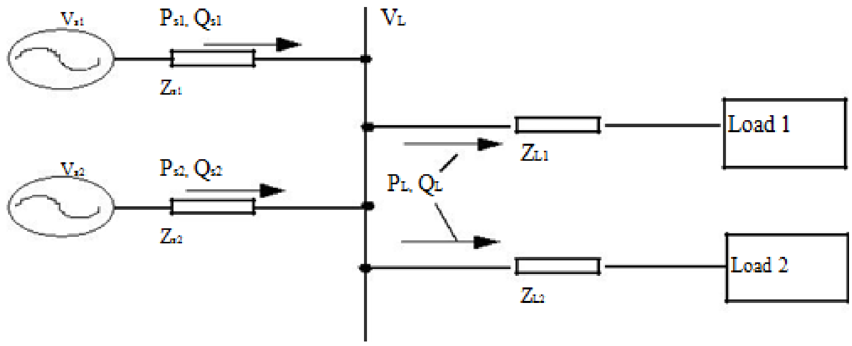

Fig. 22 Block Diagram of the Example System

7.1 Power Control in Steady State

Two of the steady state studied cases are presented. In the presented cases, the wind speed is shown in Fig. 23. The wind turbine VSC is controlled to deliver active power into the system with a unit power factor. The VSC of diesel unit/energy storage provides the reactive power required by the system and keeps the system voltage within the required range. There is a load reduction at 12 seconds of the simulation time.

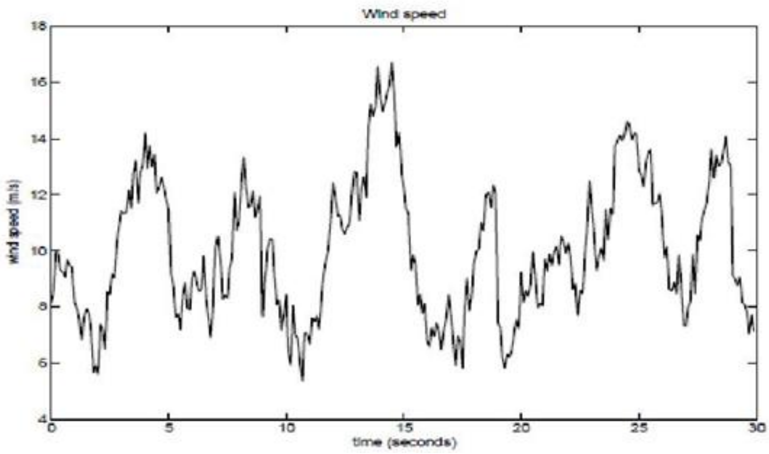

Fig. 23 Wind Speed for Case Study

Fig. 24 shows the results of the first case, and the wind turbine delivers all available power into the system i.e. the power output is not limited by a pitch control. The diesel unit with energy storage system takes both generation and absorption modes to balance the system load. Fig. 24(a) presents the system voltages as marked in Fig. 22, and it can be seen that the load voltage is kept almost constant, while the terminal voltage of the wind turbine varies in order to deliver the power generated by the turbine. Fig. 24(b) gives the active power of the system. Since the active power of the wind turbine is not limited, the wind power is possibly higher than the load consumption, and then the energy storage system can be charged, which corresponds to the period that Ps1 becomes negative. The system reactive power is shown in Fig. 24(c), and it can be seen that the reactive power

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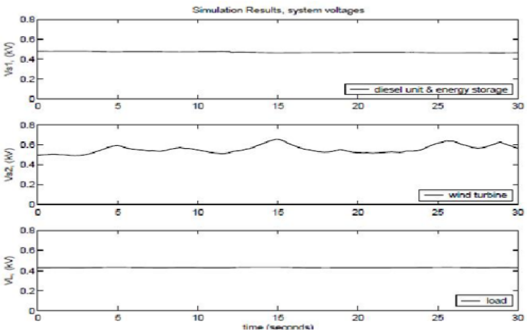
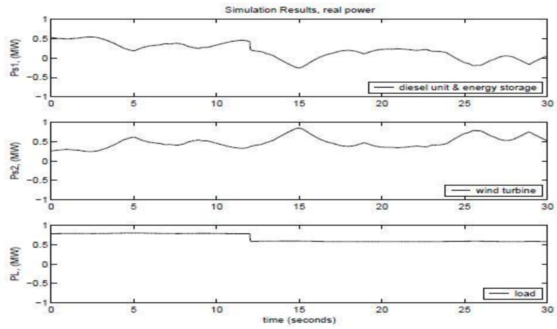
of the diesel unit is equal to the reactive power consumed by the load while the reactive power from the wind turbine is zero.

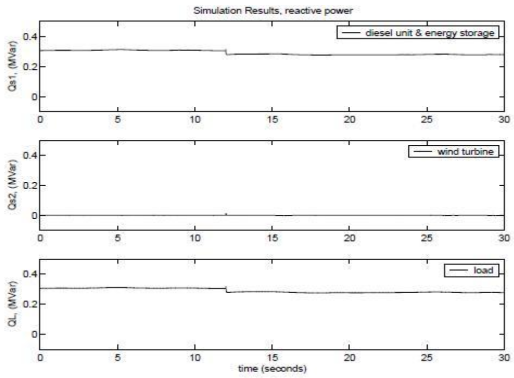
The second case is shown in Fig. 25. Here the power from the wind turbine is limited so as not to exceed the power consumed by the load; which corresponds to the situation where the energy storage device cannot take more energy. Therefore, the pitch control is used to reduce the power of the wind turbine. Fig. 25(a) presents the system voltages. Again, it can be seen that the load voltage is kept almost constant. Also, the variation of the voltage at the terminal of the wind turbine is reduced in comparison with the previous case, since the peak power is limited. Fig. 25(b) gives the active power of the system. Since the active power of the wind turbine is limited, the wind power is equal to the load consumption in some periods, then the VSC of diesel unit/energy storage system works as a reactive power compensator to produce reactive power only as shown in Fig. 25(c). Again, the reactive power from the wind turbine is zero.



(a) system voltage (case 1)

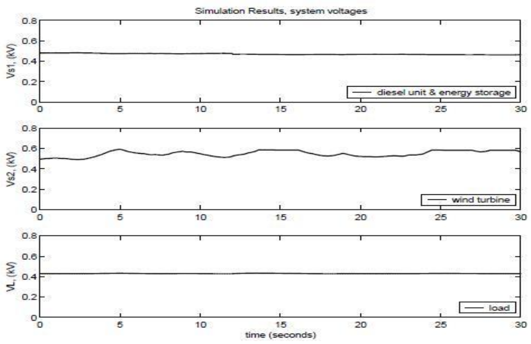


(b) System active power (case 1)

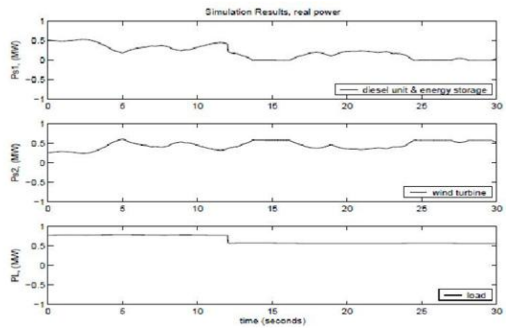


(c) System reactive power (case 1)

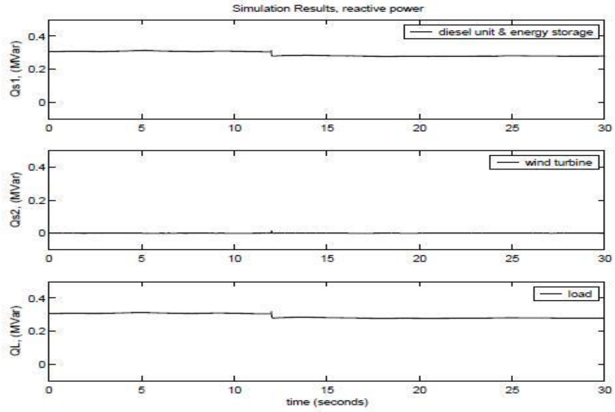
Fig. 24 Case of Energy Storage System Taking Power From Wind Turbine



(a) System voltage (case 2)

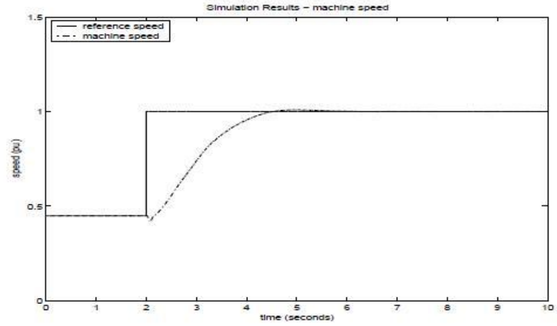


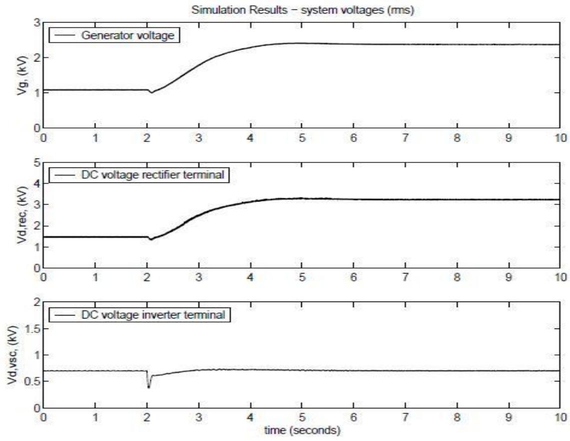
(b) System active power (case 2)



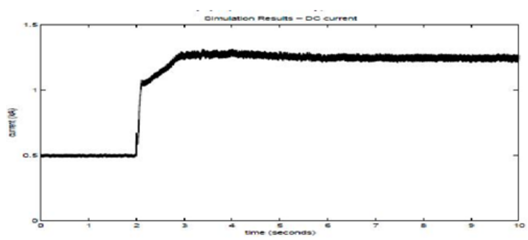
(c) System Reactive Power (case 2)

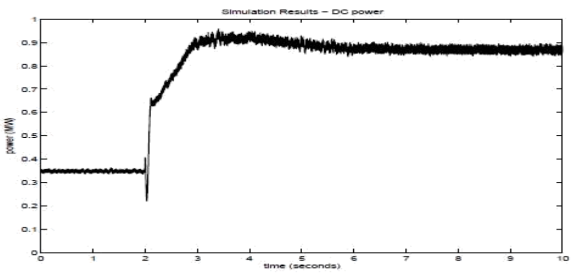
Fig. 25 Case of Wind Turbine Limiting the Output





(a) Machine spped **(b) system voltages**





(c) DC link current **(d) DC link power**

Fig. 26 Simulation Results (Rms Values)

The presented dynamic study cases are focused on the system behavior of diesel generation unit and its control system under a load increase, which results in that the loading level of the diesel generation unit is doubled.

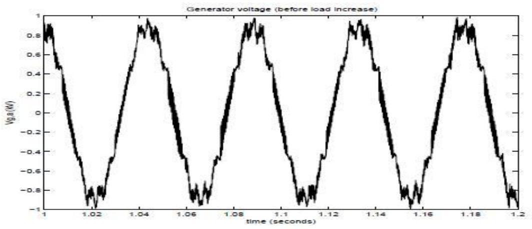
7.2 Power Control of Diesel System in Dynamics

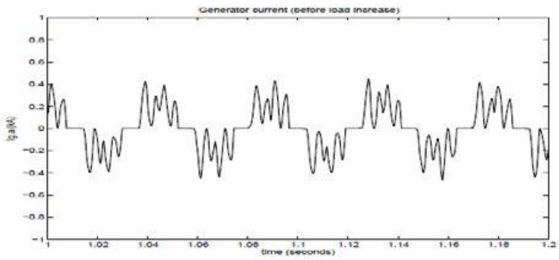
Before the load changes, the diesel system operates at a speed of 0.45 pu;at 2.0 seconds of the simulation time, a load is switched in. Assume that the needed power due to the load increase is to be carried by the diesel engine, therefore a new reference speed is generated by the controller, and then the fuzzy controller adjusts the speed of the diesel unit. The generator speed is increased and stabilized at the new reference speed as shown in Fig. 26

(a) . It can be seen that the fuzzy controller works well in the speed control of the diesel generation unit. Since the generator is a permanent magnet machine, the generated voltage is in proportion to the speed; whichcan be clearly seen in curve 1, Fig. 26 (b). Also the dc voltage at diode rectifier terminal, curve 2 in Fig. 26 (b), presents the same pattern. The curve 3 in Fig. 26 (b) is the dc voltage at the VSC terminal. It can be seen that the dc chopper quickly restores the voltage to the rated level though the generator voltage is still in variation. Fig. 26 (c) shows the dc link current.

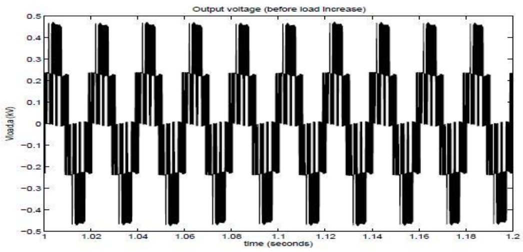
Figs. 27 and 28 present the system waveforms in the states before and after the load disturbance. Fig. 27 shows the waveforms at the lower power level operation condition before the load increases. Figs. 27

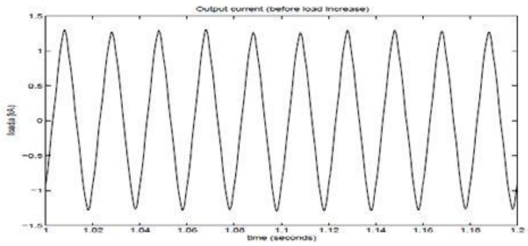
(a) and (b) are the generator voltage and current, Figs. 27 (c) and (d) are the voltage source converter voltage and current, and Fig. 27 (e) is the dc link current.



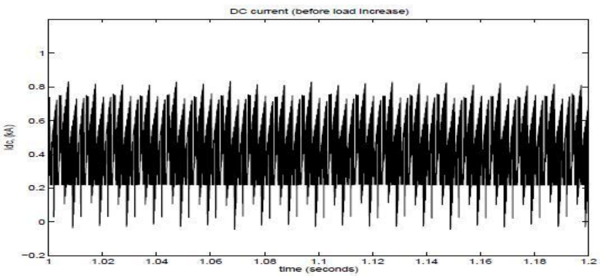


(a) Generator Voltage (Before Load Increase) (b) Generator current (before load increase)





(c) load voltage (before load increase) (d) load current (before load increase)



(e) DC link current (before load increase)

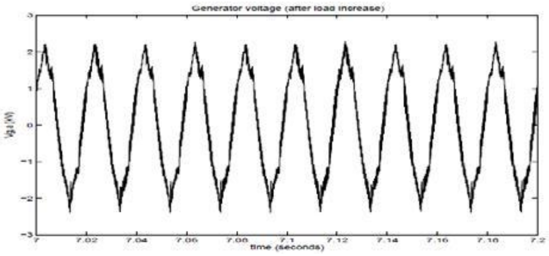
Fig. 27 Simulated Waveforms (Before Load Increase)

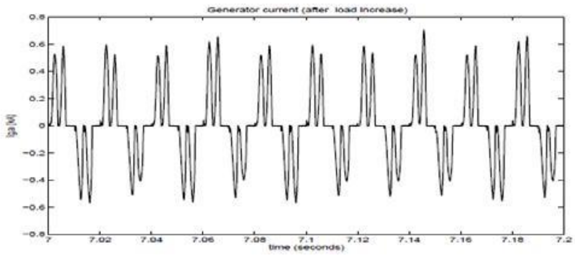
In comparison, Fig. 28 shows the corresponding waveforms at the higher power level operation condition after the load increases. Figs. 28 (a) and (b) are the generator voltage and current, Figs. 28 (c) and

(d) are the voltage source converter voltage and current, and Fig. 28 (e) is the dc link current.

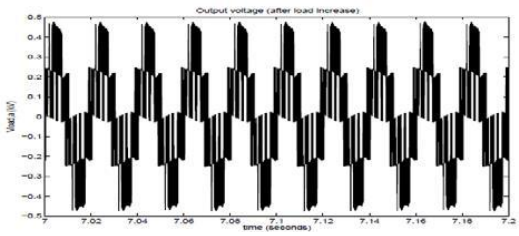
Comparing the generator voltages and currents in Figs. 27 (a) and (b) with Figs. 28 (a) and (b), it can be seen that the frequency of the voltage and current is almost doubled in Fig. 28. It is also noted that the voltage and current contains harmonics at the generator side due to the capacitive type of dc link of the diode rectifier.

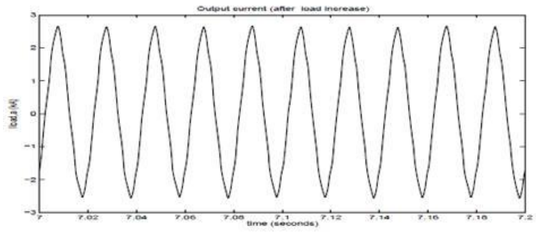
PWM phase voltage waveforms at the ac terminal of the voltage source converter in Figs 27 (c) and 28 (c) have the similar pattern and magnitude. It can be seen that the ac current is doubled by comparing Fig 27 (d) with Fig. 28 (d).



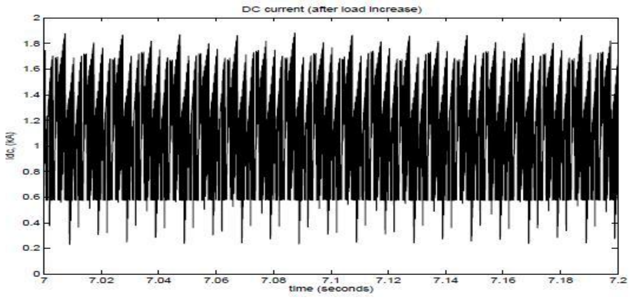


(b) Generator voltage (after load increase) (b) Generator current (after load increase)





(c) load voltage (after load increase) (d) load current (after load increase)



(e) DC link current (After Load Increase)

Fig.28 Simulated Waveforms (After Load Increase)

The dc currents before and after the load increases are given in Figs 27 (e) and 28 (e) where the switching ripples and the increase of the transferred power can be observed.

VIII. CONCLUSIONS

The paper presents an autonomous power system consisting of the wind turbines, diesel generation units and energy storage devices. Both the wind power generator and the diesel generator are connected to the ac load system through power electronics interfaces and operate at variable speed so as to maximize the wind energy capture and minimize the diesel fuel consumption.

The system characteristics are presented and the operation schemes are discussed. The control system and control strategies are developed and a fuzzy diesel power controller is used. Both steady state and dynamic studies are performed by simulation.

The simulation studies have demonstrated that the studied system can effectively provide good quality power to the customers in the autonomous power system and that the quick control ability of the converters plays a key role in improving the system dynamic performance and enhancing the system stability.

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