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HYBRID POWER FILTER FOR POWER QUALITY IMPROVEMENT IN RAPS

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Abstract:* Remote area power system (RAPS) becoming an emerging technology for rural area and hill stations. Standalone operation of a wind turbine generating system under fluctuating wind and variable load conditions is a difficult task. Moreover, high reactive power demand makes it more challenging due to the limitation of reactive capability of the wind generating system. A Remote Area Power Supply (RAPS) system consisting of a Permanent Magnet Synchronous Generator (PMSG), hybrid energy storage, a dump load and a mains load is considered in this paper. The hybrid energy storage consists of battery storage and a super capacitor where both are connected to the DC bus of the RAPS system. An energy management algorithm (EMA) is proposed for the hybrid energy storage with a view to improve the performance of the battery storage. A shunt active power filter (SAPF) is employed to provide harmonic mitigation and reactive power compensation and inertial support to the RAPS system. A SRF theory with approach with hysteresis control technique is developed to manage the active and reactive power flows among the RAPS components with minimized harmonics. In this regard, individual controllers for each RAPS component have been developed for effective management of the RAPS components. Through simulation studies carried out using detailed model in MATLAB Simulink, it has been demonstrated that the proposed method is capable of achieving: a) robust voltage and frequency regulation b) effective management of the hybrid storage system, c) reactive power capability and harmonic mitigation support by shunt active power filter (SAPF), and d) maximum power extraction from wind with the help of P&O MPPT algorithm.

Index Terms:* Battery storage, hybrid energy storage system, permanent magnet synchronous generator, remote area power supply, supercapacitor and synchronous condenser.

I. INTRODUCTION

Variable nature of wind and fluctuating load profiles make the operation of wind based power systems challenging, particularly when they operate in standalone mode. The random variation of wind speed leads to fluctuating torque of the wind turbine generator resulting in voltage and frequency excursions in the Remote Area Power Supply (RAPS) system. Integration of an Energy Storage System (ESS) into a wind based power system provides an opportunity for better voltage and frequency response, especially during wind and load demand variations. The application of energy storage to a standalone power system can be used to fulfill one or more of the following requirements: To improve the efficiency of the entire RAPS system, to reduce the primary fuel (e.g., diesel) usage by energy conversion, and to provide better security of energy supply. The justification behind the integration of energy storage into a wind energy application is based on the factors which include total wind turbine inertia, low voltage ride through capability, power quality issues, etc. For a wind turbine based RAPS system, an ideal ESS should be able to provide both high energy and power capacity to handle situations such as wind gust or sudden load variations which may exist for a few seconds or even longer. However, among all the energy storage options available, a single type of energy storage is not seen to satisfy both power and energy requirements of the RAPS system thus requiring the combination of two or more energy storage systems to perform in a hybrid manner. The selection of an energy storage option requires good understanding of its operational characteristics. In general, battery and super capacitor are seen to provide high energy and power requirements respectively. Therefore, the integration of a super capacitor ensures a healthy operation of the battery storage by preventing it to operate in high Depth of Discharge (DOD) regions and to operate at low frequency power regions. Permanent Magnet Synchronous Generator (PMSG) offers many advantages but not limited to self-excitation capability which allows operation at a high power factor and improved efficiency, gear-less transmission, high reliability, good control performance, Maximum PowerPoint Tracking (MPPT) capability, low noise emissions, etc.

II. REMOTE AREA POWER SYSTEM

Wind energy conversion system based on PMSG is used for variable wind speed operation which is part of remote area power system is discussed. It consists of PMSG based wind energy conversion system, hybrid energy storage system and hybrid filter and supervisory control technique for each part of RAPS system. The maximum potential of wind energy is utilized with the help of permanent synchronous generator with MPPT control under various wind speed condition.

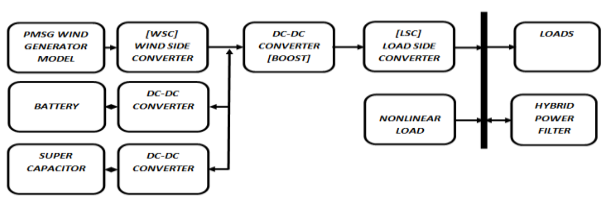

Fig. 1. Overview of RAPS system

A. Wind Energy Conversion System

In the last decade, wind power generation systems have experienced tremendous growth and been recognized as an alternative environmentally-friendly and cost-effective means of power generation. The major components of a typical wind energy conversion system (WECS) include a wind turbine, generator and control systems. Fig.1 shows a WECS. The generators conventionally used in WECSs are the doubly-fed induction generator (DFIG), cage induction generator (IG), and synchronous generators (SG). The Power electronics correspond to a back-to-back converter. The WECS can be connected to a large utility, a micro-grid (weak grid), or a stand-alone load.

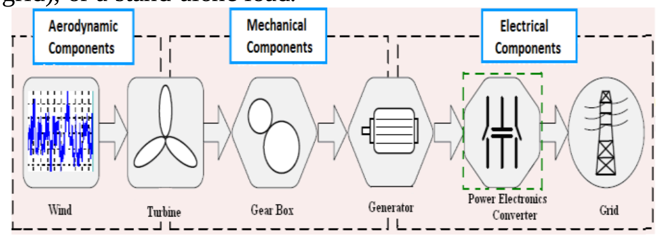

Fig. 2. Wind energy conversion system

B. Operating Region Of The Wind Turbine

The operating region of a variable-speed variable-pitch wind turbine can be illustrated by their power curve, which gives the estimated power output as function of wind speed as shown in Fig. 3. Three distinct wind speed points can be noticed in this power curve:

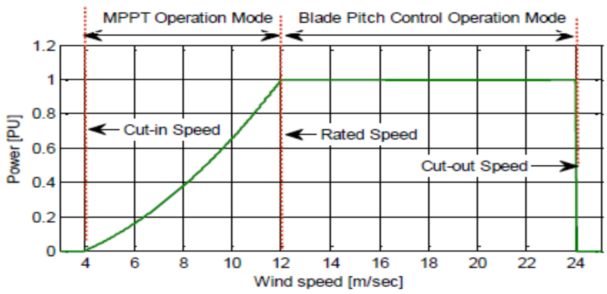

Fig. 3. Operating regions of WEC

- Cut-in wind speed: The lowest wind speed at which wind turbine starts to generate power.
- Rated wind speed: Wind speed at which the wind turbine generates the rated power, which is usually the maximum power wind turbine can produce.
- Cut-out wind speed: Wind speed at which the turbine ceases power generation and is shut down (with automatic brakes and/or blade pitching) to protect the turbine from mechanical damage.

C. Wind Turbine Generators

Wind Turbine Generators in the current market can be classified into three types according to their operation speed and the size of the associated converters as below:

- Fixed Speed Wind Turbine (FSWT)
- Variable Speed Wind Turbine (VSWT)
- Partial Scale Frequency Converter Wind Turbine (PSFCWT)
- Full Scale Frequency Converter Wind Turbine (FSFCWT)

Variable-speed variable-pitch wind turbines utilizing DFIG, also called PSFCWT, are the most popular in the wind power industry especially for multi-megawatt wind turbine generators. The converter compensates the difference between the mechanical and electrical frequencies by injecting a rotor current with a variable frequency. Hence, the operation and behavior of the DFIG is governed by the power converter and its controllers.

D. Control of Wind Turbine System

With the increase in wind turbine size and power, its control system plays a major role to operate it in safe region and also to improve energy conversion efficiency and output power quality. The main objectives of a wind turbine control system are

Energy capture: The wind turbine is operated to extract the maximum amount of wind energy considering the safety limits like rated power, rated speed.

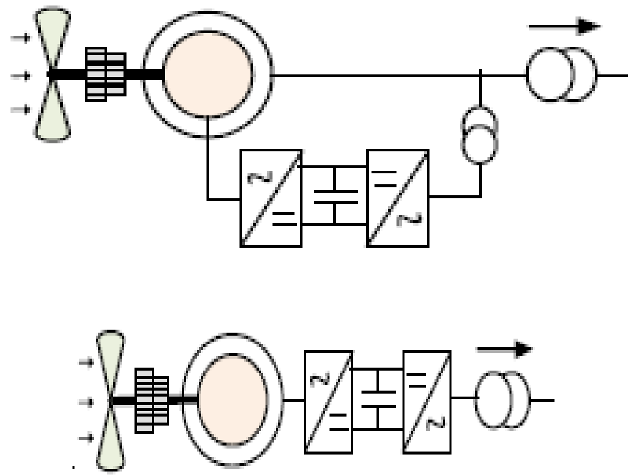

Fig. 4. Types of WEC

Conditioning the generated power with grid interconnection standards. The various control techniques used in wind turbines are pitch control, yaw control and stall control. But in the modern variable speed-variable pitch wind turbines, pitch control is the most popular control scheme. In this control scheme, the horizontal axis wind turbine blades are rotated around its tower to orient the turbine blades in upwind or down wind direction.

III. OPERATING PRINCIPLES OF PMSG

For the purpose of discerning the operating principle, a simplified representation of the steady state equivalent circuit of a non-salient pole PMSG is shown in Fig3.5. The circuit representation neglects the stator resistance. The internal voltage, E behind the inductance Ld, is given as function of rotor speed, ω_r and permanent magnet flux φ_{pm}. Further, the electromagnetic torque produced by the PMSG can be explained as in

$$T_e = i_{qs}^r \phi_{pm}^r$$

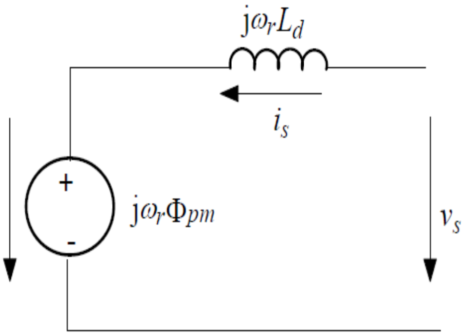

Fig. 5. Simplified model of PMSG

Considering the simplicity and reduced cost, the arrangement shown in Fig.6. Where a PMSG is connected to an uncontrolled three phase diode bridge rectifier- inverter system is employed in the present work.

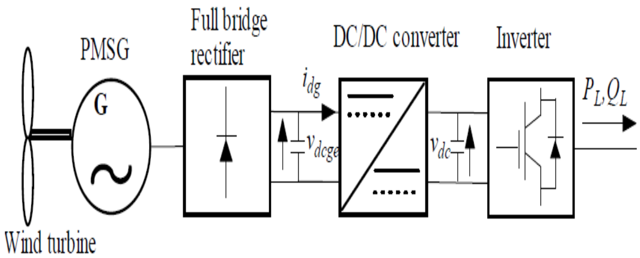

Fig. 6. Typical configuration of WEC

Unlike in a DFIG based wind generating system, total power generated by the PMSG turbine passes through the rectifier-inverter arrangement. The unregulated DC bus voltage υdcge, which appears at uncontrolled diode bridge rectifier is proportional to the speed ωgm of PMSG and hence υdcge varies in an unregulated manner. Therefore, a DC/DC converter21 is connected to regulate the DC bus voltage υdc of the system.

A. Inverter Control Of PMSG

Noting that the PMSG generator is not directly connected to the load as shown in Fig, its excitation mechanism is not important for voltage regulation on the load side in comparison to a DFIG. It is therefore not the generator that supplies the reactive power required by the load and controls the load side voltage but the inverter. Noting these facts, the inverter control associated with the PMSG is used to regulate the magnitude of the AC voltage and frequency of the RAPS system. In this regard, a control algorithm has been developed considering the voltage balance across the filter circuit similar to the case of inverter. However, in this case the inverter is modeled as a voltage controlled voltage source inverter as its main objective is to control the load side voltage. Moreover, to achieve the decoupled control, the q-axis component of the stator voltage υqs is made equal to zero. In addition, the angular velocity ω, of the rotating axis system is defined using a virtual PLL. All PI controllers associated with inverter control scheme are tuned using the internal model control principle as described in

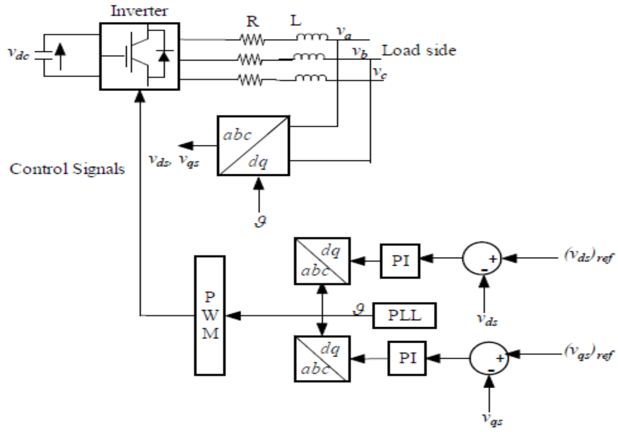

Fig.7. Inverter control of PMSG based RAPS system

B. DC/DC Converter Control

As shown from Fig, the output voltage υdcge of full bridge rectifier varies in an uncontrolled manner. Therefore, a DC/DC converter is included which transforms the unregulated DC link voltage to a regulated value. In this regard, a buck or boost converter can be used to interface with the DC bus. Selection of buck or boost converter configuration depends on the output voltage υdcge that appears at the output of the uncontrolled diode rectifier. The operating terminal voltage range of the PMSG can be easily determined considering the voltage constant which is usually provided by the machine manufacturer.

C. MPPT Control Methods For PMSG Based WECS

Permanent Magnet Synchronous Generator is favored more and more in developing new designs because of higher efficiency, high power density, availability of high-energy permanent magnet material at reasonable price, and possibility of smaller turbine diameter in direct drive applications. Presently, a lot of research efforts are directed towards designing of WECS which is reliable, having low wear and tear, compact, efficient, having low noise and maintenance cost; such a WECS is realizable in the form of a direct drive PMSG wind energy conversion system. Depending upon the power electronics converter configuration used with a particular PMSG WECS a suitable MPPT controller is developed for its control. All the three methods of MPPT control algorithm are found to be in use for the control of PMSG WECS.

D. Maximum Power Extraction From Wind

Not all kinetic energy available from wind can be extracted by a wind turbine and hence power coefficient Cp is defined which is a function of tip-speed ratio λ, and pitch angle β is employed. Therefore, power captured from a wind turbine is given. The maximum power from wind can be obtained when a wind turbine is operated at its optimum power coefficient. This can be achieved by operating the turbine at a desired speed to obtain the optimal tip-speed ratio λ given.
The MPPT from wind without considering the Wind turbine power characteristics with maximum power extraction,

where the optimized constant k is given. In power losses of the system due to frictional losses, resistive losses in stator and rotor and losses associated with power electronics1 devices have also been considered when implementing the maximum power extraction algorithm for each RAPS systems. However, in this paper an approximate method considering the efficiency associated with the power electronic devices have been used to estimate the corresponding power electronic device losses. The typical turbine power characteristics and its MPPT curve described in are shown in Fig. 8.

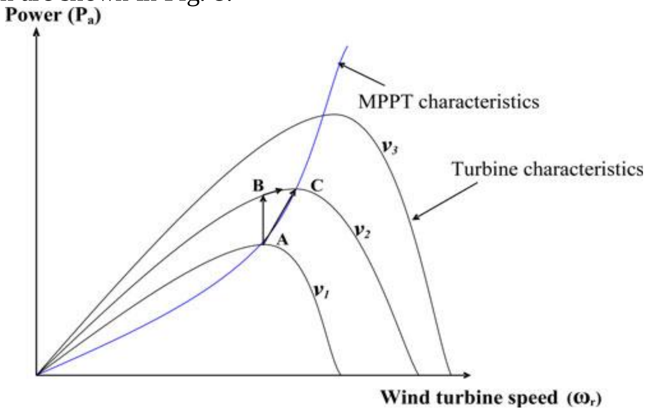

Fig. 8. Wind turbine power characteristics with maximum power extraction.

For the purpose of illustration of the MPPT principle, assuming that wind turbine generator operates on its maximum power curve, the wind turbine generator initially operates at point A when the wind speed is v_1. If the wind speed changes from v_1 to v_2 , then the turbine changes its power output from A to B. The wind generator cannot respond to this wind speed change quickly due to the inertia associated, thus retains the same electrical power (i.e., power at point A). As a result, the mechanical power input from the turbine to the generator is greater than its electrical power, causing the wind generator system to accelerate. This acceleration would lead mechanical power to follow the path from B to C (B → C) while generator power from A to C (A → C). Finally, the system becomes stable at point C. Further details on stability of a wind turbine around its optimal operating curve can be found. The maximum power extraction from wind (P_w) is obtained using the indirect speed control technique.

IV. ENERGY STORAGE SYSTEMS FOR WIND POWER APPLICATIONS

Due to the variable nature of wind (i.e. intermittency), a wind turbine generator alone cannot supply power to loads due to its inability to match the load demand. In this regard, a wind farm to be dispatch able similar to other conventional generation units such as a diesel generator, the generated power has to be regulated at a desired level. With rapid developments currently taking place on energy storage devices, their application in wind energy systems is seen to provide a promising opportunity to mitigate the issues associated with wind power fluctuations as shown by Fig3.9.

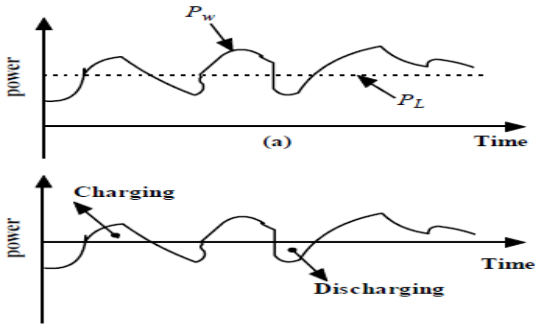

Fig. 9. Application of energy storage in a WEC system

An energy storage system can be categorized in terms of its role in a RAPS power system: either for energy management or for power quality enhancement. These two objectives can be further explained using the following sub-objectives.

- To improve the efficiency of the entire system.
- To reduce the primary fuel (e.g. diesel) usage.
- To function as an alternative source or a buffer in the absence of other types of components (e.g. diesel generators, dump loads etc.).
- To provide better security and enhanced power quality of energy supply.

A. Types And Sizing Of Energy Storage Systems

An ideal energy storage system in a standalone WECS should be able to provide both high energy and power capacities to handle situations such as wind gusts and load step changes which may exist for seconds or minutes or even longer. At present, various types of storage technologies are available to full either power or energy requirements of a RAPS system. Widely advocated energy storage technologies that currently employ in wind farms are: batteries, super capacitors, flywheel, compressed air energy storage, hydro pumped storage, superconducting magnetic energy storages (SMES), fuel cells etc. The power and energy density ranges associated with these energy storage systems are shown in Fig.

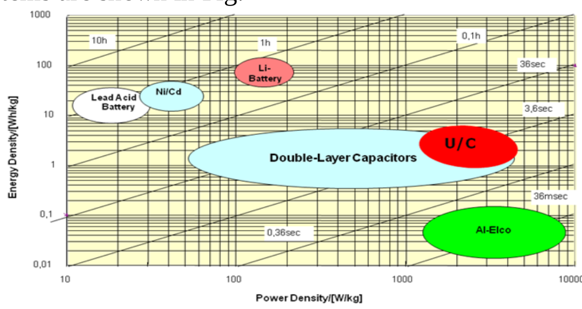

Fig. 10. Specific energy versus specific power ranges for various energy storage systems.

Energy storage systems with high energy density levels are usually termed as “long term storages” as they are able to operate over a long period of time (e.g. minutes to hours). Similarly, energy storage systems with high power density are termed as “short term storages” as they are capable of handling the transients which occur over a short periods of time (e.g. seconds to minutes) Among all energy storage systems depicted in Fig.3.10.electrochemical batteries are seen to have the highest energy density while the super capacitors seem to have the highest power density. In principle, the energy storage requirement in a RAPS system could be provided either by a battery or a super capacitors system due to their inherent high power and energy capacities over other types of storage systems. At present, battery with super/ultra capacitor energy storage systems are widely employed in most real life RAPS applications. The comparison between battery and super capacitors are shown in below fig3.11.

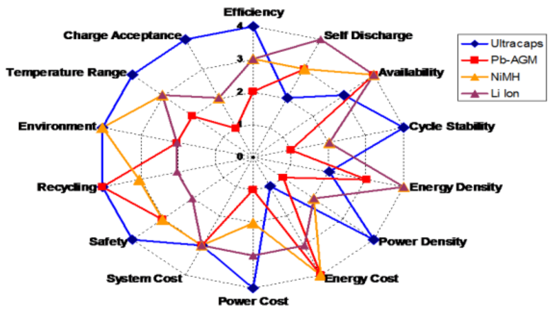

Fig. 11. Performance comparison

In this way, the combined energy storage system is able to satisfy both power and energy requirements of the RAPS system.

B. Synchronous Condenser

In the RAPS system the PMSG inverter control may not be able to provide robust voltage control especially when it needs to serve reactive power loads. This is mainly due to the capacity limitation associated with the inverters. Moreover, the PMSG is fully decoupled from the power electronic arrangement (i.e., through rectifier and inverter arrangement). Therefore, the PMSG has no inertia contribution towards the inertial requirement of the entire RAPS system. In this regard, to provide enhanced reactive power together with inertial support, a synchronous condenser can be incorporated into the RAPS system.

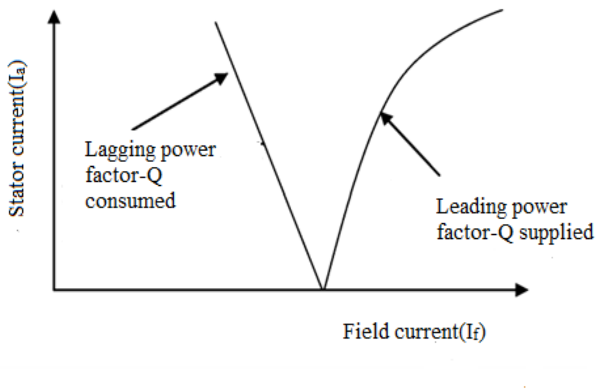

Fig. 12. V curve of synchronous condenser.

In this, the synchronous condenser is used to operate at leading power factor region to supply reactive power into the RAPS system.

C. Dump Load

The dump load is coordinated with the hybrid energy storage system to maintain the active power balance of the system. In practical RAPS systems, a dump load can be a space-heating or water-heating system. In this paper, the dump load is represented by a series of resistors which are connected across switches. The resistors operate at zero crossings of the load side voltage to ensure minimum impact on the system voltage quality. The maximum power that can be dissipated through a dump load. A simplified control schematic diagram of the dump load controller is shown in Fig.14. where is the number of three phase resistive elements, and is power that can be absorbed per resistor step.

To demonstrate how the rating of the dump load is estimated, assume that and (i.e., number of three phase resistive elements present in the dump load). For this condition, the size of the dump load will be as below:

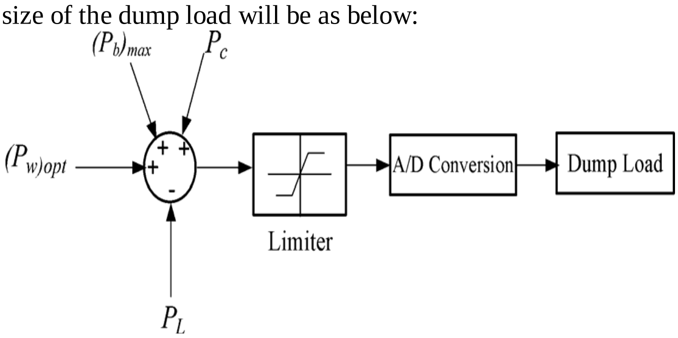

Fig. 13. Dump Controller

A dump load is also incorporated into the DC link of the system. In this case, the dump load is used to regulate the DC-link voltage in situations where the battery storage system is not in operation due to reaching its maximum storage capacity. The dump load is represented by a DC resistor which is connected via a switch. The dump load is coordinated with the battery storage to maintain the power balance of the RAPS system and to extract maximum power from wind. The control structure of the dump load developed by the authors in an earlier work has been employed for the PMSG-based RAPS system. A simplified control scheme associated with the dump load. The dump load is modeled as a set of three phase resistors which is connected across switches. The power imbalance associated with the RAPS system is selected as the input signal to the controllers of the dump loads which is converted into digital signals and is fed into the switches.

V. POWER QUALITY IN RAPS

The remote area power system is affected by various problems like transients, noise, voltage sag/swell, which leads to the production of harmonics and affect the quality of power delivered to the end user. The harmonics may exist in voltage or current waveforms which are the integral multiples of the fundamental frequency, which does not contribute for the active power delivery. Thus the response at these frequencies should be restricted from affecting the behavior of the system. To achieve this filter is used at the Point of Common Coupling (PCC) where the load is connected to the supply. This filter filters out the harmonics and improves the performance of the system. Any power problem that results in failure or disoperation of customer equipment manifests itself as an economic burden to the user, or produces negative impacts on the environment. Any power problem that is due to voltage, current or frequency deviation defines power quality. It also results in the failure of customer requirement. Poor power quality can result in lost productivity, lost and corrupt data, damaged equipment and early failure of equipment. There are three key aspects of power quality power factor, harmonics and disturbance. Among these harmonic distortion is the most severe problem. Harmonic distortion is mainly due to the electronic loads (i.e. nonlinear loads). As a result, power conditioning equipments are becoming very essential for the customer utilities.

A. Control Strategies/Algorithms

In any active power filter system, control algorithms has major role in deciding the performance of harmonic compensation. The gate pulses provided are provided using the control algorithms to the voltage source inverter used in filtering system. It makes a closed loop control on the harmonic current present in the line and compares with ac sinusoidal source to get the error. This error is passed through some controllers and control algorithms to generate pulses for VSI. The reliability and performance of any active power filtering largely depend on control algorithms adopted, there are number of algorithms proposed in the last decade some of which work good under balanced and unbalanced conditions also. Input to the control block is source current, load current and the DC link voltage.

- The performance of compensation of harmonics of source current largely depend on the algorithm adopted since the control methods are responsible for generating the reference currents which used to trigger the Voltage Source Inverters (VSI).
- The APF needs an accurate control algorithm that provides robust performance under source and load unbalances.
- Better control strategy leads to better dynamic response of the system.

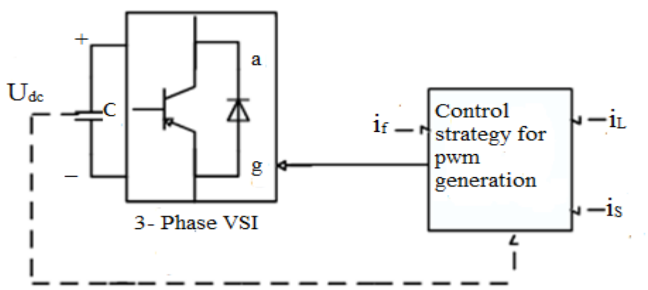

Fig. 14. Control strategy of HAPF

B. Fundamental Component Calculation

A Low pass filter (LPF) is used in the fundamental calculation block to filter out the harmonics and extract the fundamental component. A comparison is made between the actual and reference values of the output voltage of APF. The error is passed through a PI controller. The gain values of the controller are tuned in such a way that the error is zero and the actual value matches almost with the reference value. If this condition is achieved perfectly then the hybrid shunt APF improves the quality of power generated to the load by filtering out the harmonics and thus improving the performance of the RAPS system.

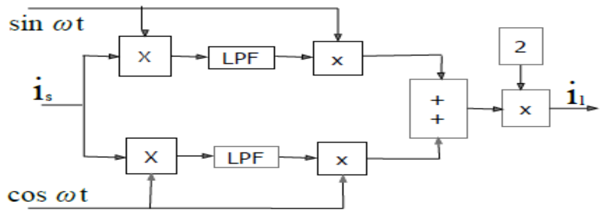

Fig. 15. Fundamental component calculation

This chapter deals with the control of the hybrid Active Power Filter. It explains how the APF is controlled such that the power quality is improved. The mathematical model of the shunt APF is derived and the generation of the reference voltage vector is explained in detail. The control algorithm is based on Instantaneous reactive power Theory. The overall control algorithm is designed such that the compensating equipment (filter) and the load together act as a resistive load on the supply system.

VI. SIMULATION RESULTS AND DISCUSSIONS

Matlab /simulink model of remote area power system (RAPS) based on hybrid energy storage system is shown in below. It consists of PMSG model, wind side converter, dc-dc boost converter with MPPT control, load side converter, hybrid energy storage system, on linear load and hybrid power filters. Wind energy from the atmosphere is converted into mechanical energy with good aerodynamic efficiency with the help of wind turbine. The mechanical output from wind turbine is given to PMSG generator of WEC system. the output of PMSG would be variable frequency and variable voltage. Output of PMSG is converted into fixed dc with the help of wind side converter.

Wind turbine parameters:

TABLE-1 Wind Turbine Parameters

Wind generation parameters	*Values*
Mechanical power	85Kw
Base wind speed	12m/sec
Pitch angle	0 deg
Generator type	PMSG
Output voltage	400Vrms
No of phases	3

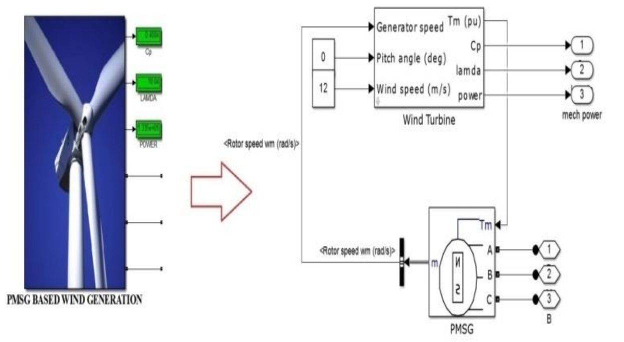

Fig. 16. Simulink model: PMSG based WEC

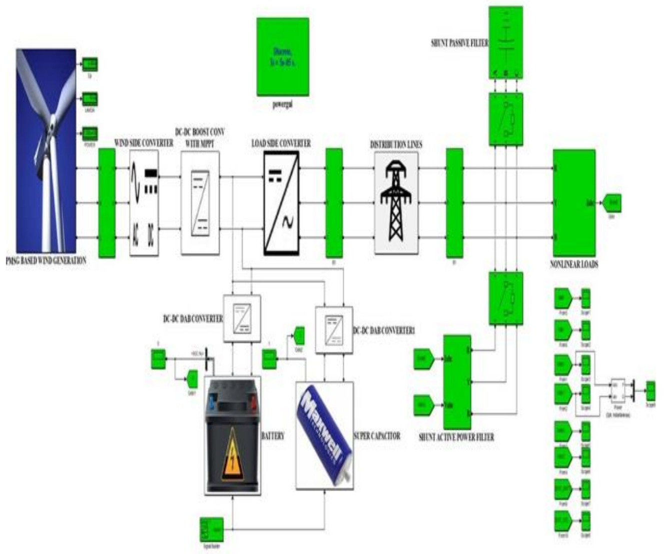

Fig. 17. Simulation model of RAPS without filter

TABLE-2 HESS And Converter Parameters

Parameters	Values
Voltage	400v:12v
Switching frequency	10KHz
Source inductance	27.6Uh
Turns ration of HF transformer	40:1
Filter capacitor	2200uF
Battery capacity	12v,10Ah
Ultra capacitor capacity	12v,500F

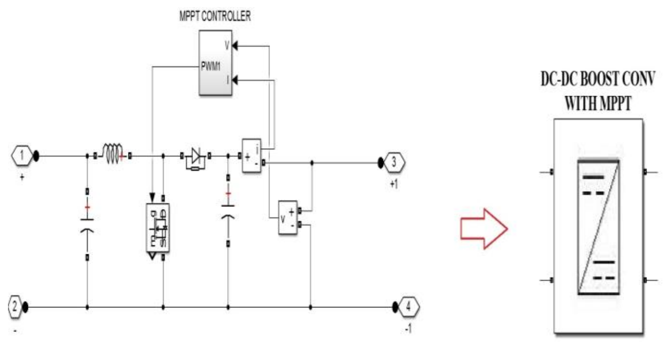

Fig.18. DC-DC converter with MPP control

Output from wind side converter is given to dc-dc converter to extract maximum power from the PMSG based wind generator with the help of P&O MPPT algorithm.

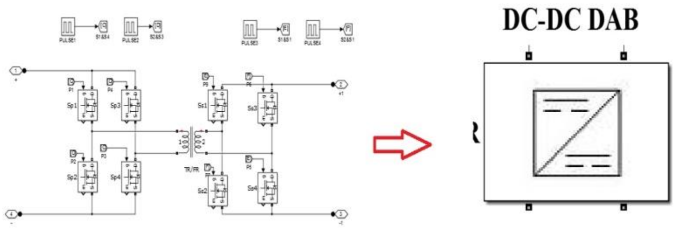

Fig. 19. DC-DC DAB converter

Here the dual active bridge dc-dc converter is used to transfer power from WEC to HESS and HESS to load to perform energy management depends upon availability of generation capacity and load demand.

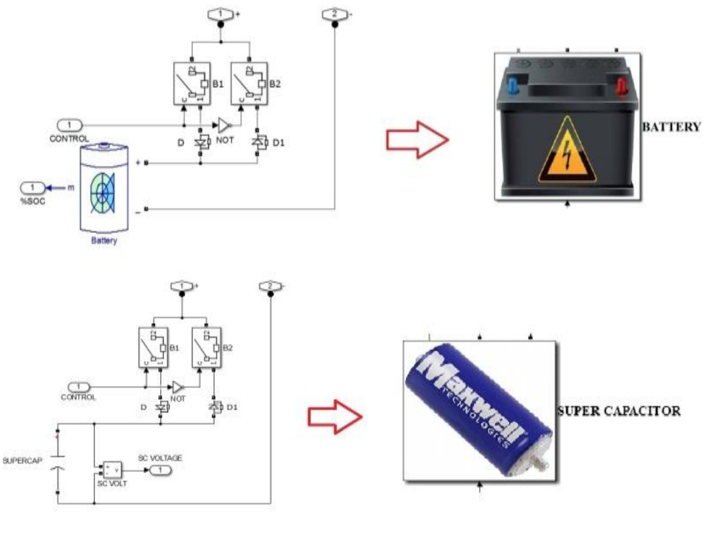

Fig. 20. Hybrid energy storage system

It consists of battery and ultra capacitor to store the electrical energy depends upon the availability. In normal working condition, partial power from the WEC system is stored into battery. In cut away wind speed condition, the excessive power transferred to ultra capacitor. It acts as dump load for WEC system.

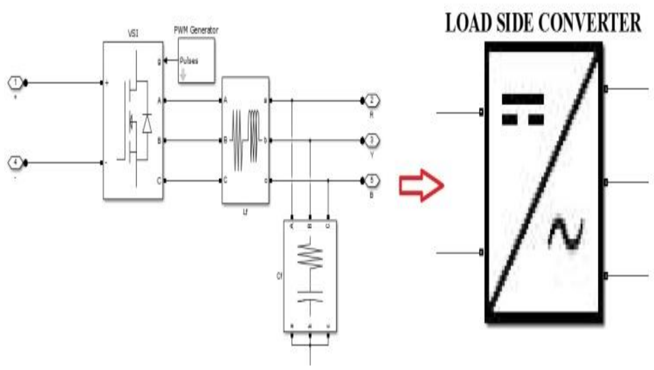

Fig. 21. Load side converter with passive filter

Load side converter with passive filters is shown in fig.4.6. it is used to convert dc into fixed frequency ac and supplied to local residential system which consists linear and non linear loads.

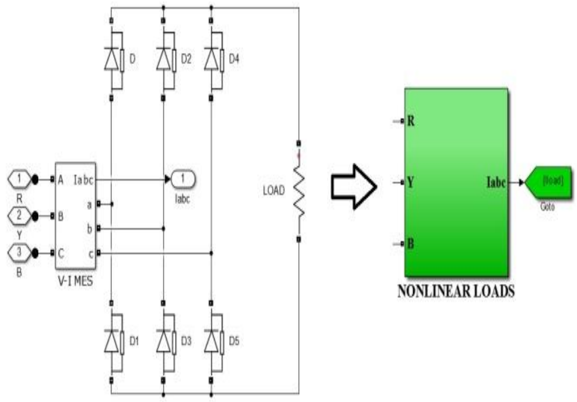

Fig.22. Non linear load

Simulink model of non-linear loads is shown in fig5.7. In general, semiconductor devices consumes non linear current which produces power quality problems such as harmonics flicker etc. among these power quality issues harmonics produces severe problems such as heat and mechanical vibration in consumer equipments. So the power factor of RAPS system affected. To minimize the impact of harmonics caused by non linear loads in RAPS system, hybrid power filters are used, which is shown in Fig.23.

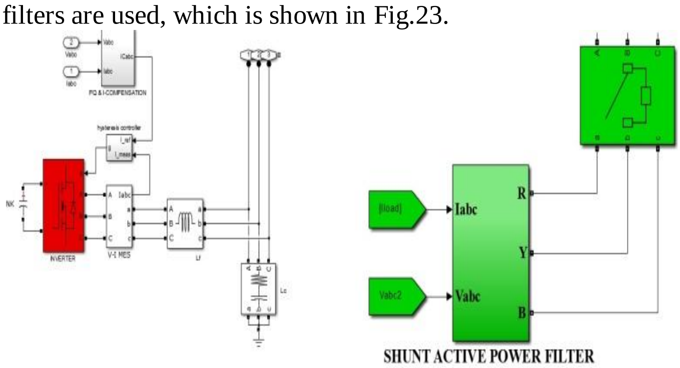

Fig. 23. Hybrid shunt power filters

It consists of both shunt type active and passive filters to minimize harmonics and reactive power compensation in wind based RAPS system.

A. Simulation Results

The simulation results of RAPS system without and with hybrid shunt filters are shown in below.

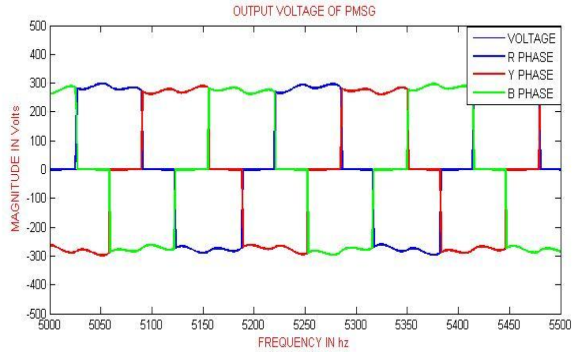

Fig. 24. Output voltage of PMSG

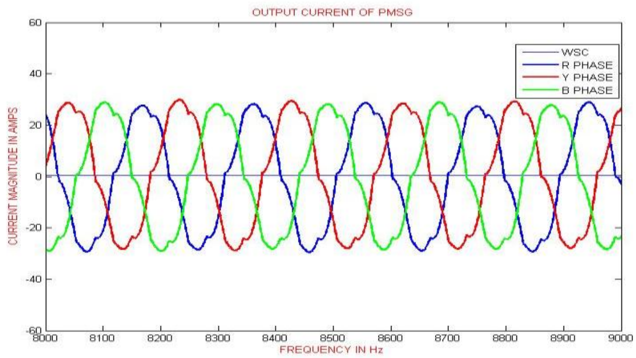

Fig. 25. Output current of PMSG

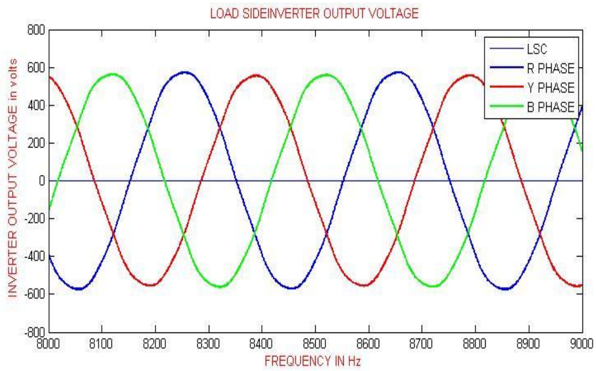

Fig. 26. Output voltage (load) of load side converter

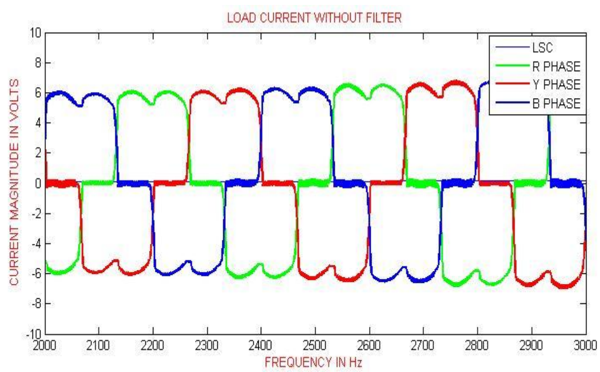

Fig. 27. Load current without filter

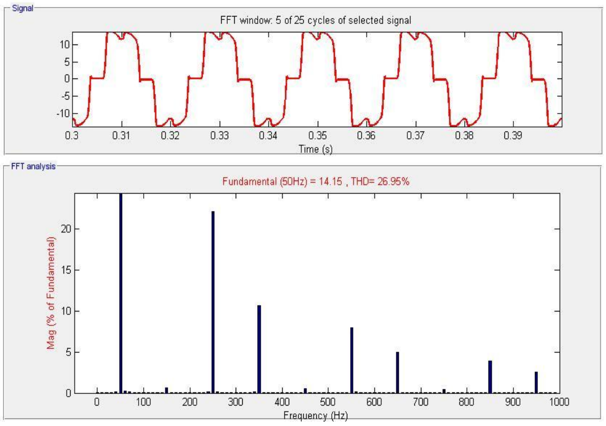

Fig. 28. THD analysis of load current without filter

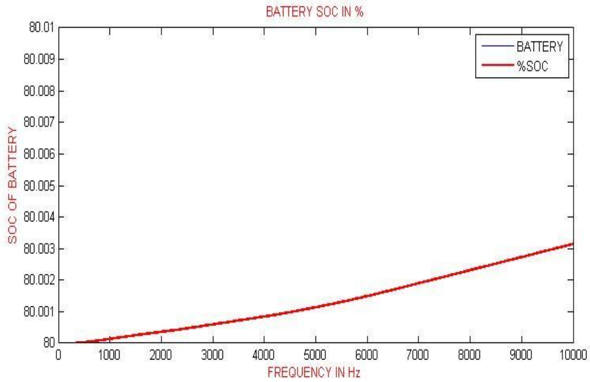

Fig. 29. SOC of battery

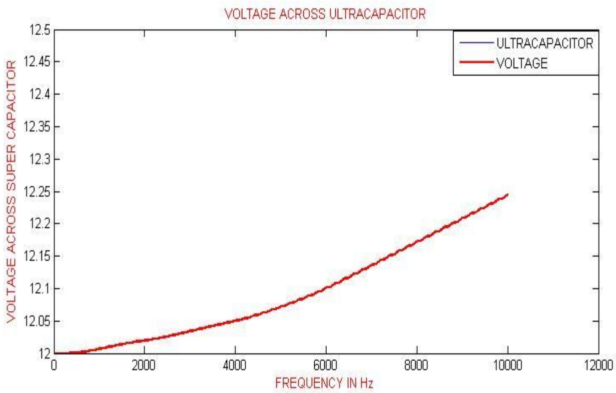

Fig. 30. Voltage across ultra capacitor

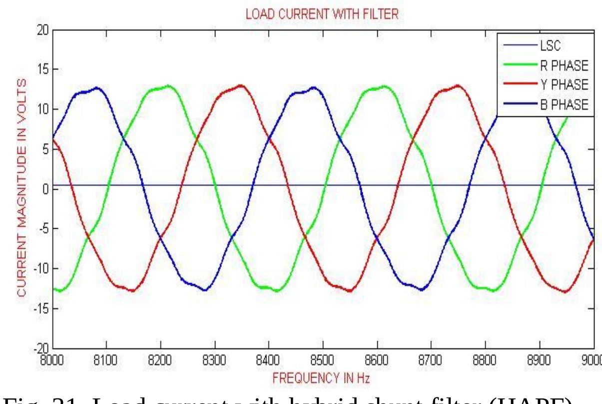

Fig. 31. Load current with hybrid shunt filter (HAPF)

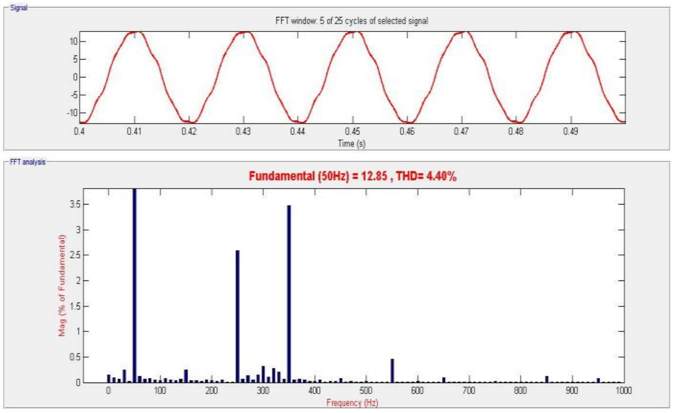

Fig. 32. THD of load current with HAPF

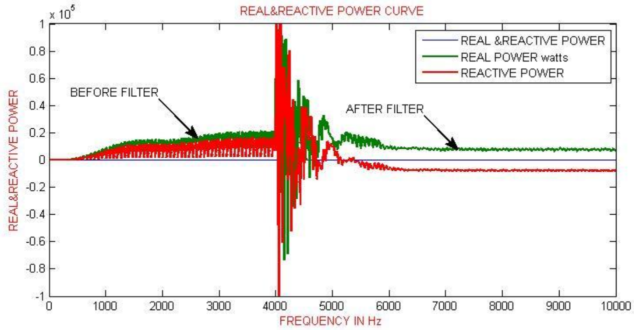

Fig.33. Real & reactive power flow

B. Result Comparison

TABLE-3 Results Comparison

PARAMETERS	RAPS without HAPF	RAPS with HAPF
Load voltage	350Vrms	350Vrms
Load current	6A	13A
Power at load	2.1Kw	4.55kW
Total harmonic distortion in %	26.95%	4.40%
Power factor	0.90	0.99

This chapter presents the MATLAB/ SIMULINK results of the proposed control strategy at different operating conditions. The system is simulated with filter and without filter. And also the behavior of the both system is compared. From the results it is inferred that the Active Power Filter is very helpful in improving the power quality of the system by filtering out the harmonics.

VII. CONCLUSION AND FUTURE SCOPE

This project has investigated the standalone operation of a PMSG with a hybrid energy storage system consisting of a battery storage with a super capacitor, and hybrid shunt active power filter. The entire RAPS system is simulated under. The suitability of the adopted control strategy for each system component is assessed in terms of their contributions towards regulating the load side voltage and frequency. Investigations have been carried out in relation to the voltage and frequency regulation at load side, DC bus stability, maximum power extraction capability of wind turbine generator and the performance of the hybrid energy storage system. From the simulated behavior, it is seen that the proposed approach is capable of regulating both voltage and frequency by reducing total harmonic distortion (THD) within permissible limit. Also, the performance of the battery storage is improved with the implementation of the proposed energy management algorithm, as super capacitor absorbs the ripple or high frequency power component of demand generation mismatch while leaving the steady component for the battery storage. With the integration of hybrid power filters (HPF),it has been proven that the RAPS system is able to maintain the load voltage within acceptable limits for all conditions including the situation when reactive power demand becomes very high with high demand of non sinusoidal current.The further research could be based on components and converter reductions in RAPS system. Multiport dc-dc converter becomes a promising technology which is very suitable for bidirectional power flow between HESS with RAPS. Further we could proceed with soft computing techniques such as fuzzy logic, neural networks to improve the stability and reliability of overall RAPS system.

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