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# A Review on Power Quality Improvement in a Grid Connected Wind Energy Conversion System Using Dynamic Voltage Restorer

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**ABSTRACT**

At the distribution grade, Power quality improvement is a stipulating exigency these days. Due to the augmentation of power generated by wind farms and the progress of non-linear loads, endowing quality power is mandatory. Voltage sag and swell prevails as the most crucial power quality issue in the system. This review article discourses the application of various controllers for Dynamic Voltage Restorer (DVR) to improve the power quality in a grid connected wind energy conversion system (WECS). DVR is the series connected custom power device (CPD) to remunerate voltage based distortions. Modern electronics devices are tremendously sensitive to power and quality problems. DVR is the most effective and efficient modern CPD conditioned and exerted in power distribution networks to minimize sag and swell conditions in the WECS.

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## INTRODUCTION

With the increase in the development of the renewable energy sources, wind energy is the upcoming tradition in this contemporary world. Many countries have developed wind energy conversion system plants for the generation of electric power. Incorporation of wind farms will lead to power quality disturbances particularly at the voltage level as sag and swell and present technical challenges and requires consideration of the power quality problems. Wind generator creates disturbances in to the distribution network and is connected to the grid system. The active power produced is changed due to the variation in wind speed. Thus the absorbed reactive power and terminal voltage will be affected. In order to get rid of all these problems a custom power device called DVR is installed. It is a series compensated device applied to the transmission and distribution systems to overcome the power quality problems. The effective and efficient operation of DVR effectively vests with the controller governing it. Reduction in the power quality issues were initially accomplished by current controlled voltage source inverter (CC-VSI) (Chen, 2001). But it can limit fluctuations only at certain level. Many topologies were analyzed in (Hee-Sang, 2007) to identify the best DVR topology. This has led to complex design and tedious procedure for analysis. Realization of STATCOM endowed with battery energy storage is explained in (Lucheng Hong, 2012) and it has resulted in incorrect rating of the STATCOM. The usage of braking resistance will lead to energy loss. The transient behavior of the system is analyzed with the DVR based on minimum voltage compensation (MVC) method. The functioning is without any controller (Peng Cheng, 2012). DVR performance is good only with a controller. Further the DVR is operated and controlled with the PI controller based on the tri loop dynamic error driven control (Venkata Rama Raju, 2012). DVR along with STATCOM is also implemented for rectifying issues. But the implementation and control of both the devices will be difficult (Christian Wessels, 2011; Patrick, 2009). The control methodology for improving the low voltage ride through(LVRT) capability with the anti voltage technology using SCR is presented. This will lead to switching losses during operation (Yingdong Wei, 2011). Enhancement in power quality using DVR in curtailing the symmetrical and asymmetrical grid faults was implemented. This was experimented without controller which has led to reduced performance (Mikel Alberdi, 2011). The operation of

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DVR with PI controller along with the comparative analysis of park's transformation was also enunciated. In park's transformation the controller operates separately (i.e) it is not aligned with the system (Victor Flores Mendes, 2011). Neural network controller is used for controlling DVR to smooth nonlinear function with greater accuracy to facilitate the control law. During the earlier stages the inherent capability of NN controller with the back propagation type by implementation of the SVM is also presented in (Ibrahim 2007).

***Dynamic voltage restorer:***

A DVR is a solid state power electronics switching device which comprises of either GTO or IGBT, a capacitor bank as energy storage device and injection transformers. The basic idea of DVR is to generate a control voltage by the injecting transformer with a forced commuted converter in series to the bus voltage.

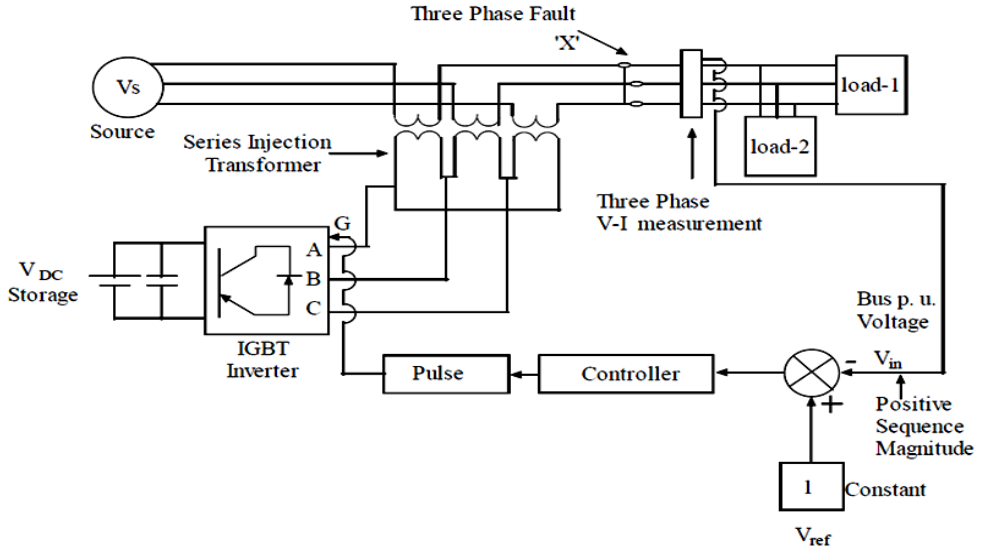


**Fig. 1:** Block diagram of DVR.

The DVR is capable of generating or absorbing reactive power but the reactive power injection of the device must be provided by an external energy source or energy storage system. The response time of DVR is very short and is limited by the power electronics devices and the voltage sag detection time. The expected response time is about 25 milliseconds, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers.

***State of the art:***

Z.Chen *et al* (2001) focused on the maintenance of the power quality in wind turbines connected to the grid. Voltage fluctuation and harmonic distortion in a network connected to the wind turbine are studied by proper modeling and discussion of the simulation techniques. Here power electronic converter i.e current controlled voltage source inverter(CC-VSI) is used as the interface. A case study reveals that the harmonics and fluctuating voltages are eliminated by the proposed power electronic system. If a large amount of power generated from a wind energy system is fed to a small network, fluctuations occur. CC-VSI has the reactive power generation ability which assists to decrease the fluctuations at certain levels. PWM switching at higher frequency meets the harmonics requirements of the system with the less expensive harmonic filter. The capability of the designed converter also serves the voltage regulation of the system. This overture is a profound study of the voltage fluctuations and harmonic distortion of the distribution network with the input from the wind energy system.

Hee-Sang Ko *et al* (2007) developed the fuzzy LQR controller for maintaining quality power in the wind-hybrid generation system. The control scheme developed is relevant to the Takagi-Sugeno (TS) fuzzy model and linear quadratic regulator (LQR). The considered wind-hybrid system is the non-linear system which is divided in to subsystems. The division is based on the framed linguistic rules. Perfectly partitioned systems are specified by the possibility auto regression model based on the time series. Each subsystem is facilitated with a controller designed by LQR. The constructed controller is compared with the classical PI controller and proved to be more efficient against disturbances from the wind turbine system. A simulation model considering the reduced -order model is derived and can be applied to various disposition of wind-hybrid power system. The conventional reduced order model only deals with the imperfections in the controller design. But the Fuzzy model compensates uncertainties providing excelling power quality.

Lucheng Hong *et al* (2012) focused on the control strategy of DVR and developed a distinct topology for increasing the ride through capability of the wind farm in wind energy conversion system. A Dynamic Voltage Restorer (DVR) pertaining to modular multilevel converters (MMC) is enunciated in this work. During the occurrence of grid fault, terminal voltage of the wind farm is affected due to voltage sag. Pulse width modulation (PWM) approach along with allied control schemes are developed to retain the terminal voltage of the wind farm at normal level. This method also enables in balancing the voltages of MMC fly capacitors and sustains voltages at PCC. A newly defined energy sharing topology is enforced to balance the three phase DC bus voltages. The modeled scheme is simulated in PSCAD/EMTDC and verified. The main advantage of using MMC is the tractable adjustment of the device based on the real time need by altering the cascaded modules.

Peng Cheng *et al* (2012) have set up a new control technique in dynamic voltage restorer applied to the wind energy system during voltage dip. The DVR scheme is modeled in DFIG system with crowbar in WECS. The proposed DVR has a distinguished connection where in which the DVR and grid side converter (GSC) share a DC capacitor. In the discussed methodology the stator voltage is prevented from changing by connecting the DVR at stator side leaving the rotor side converter(RSC).To explain the changes appeared in the stator voltage, a mathematical model of the rotor voltage is derived. Simulation results are obtained for a 1.5MW DFIG system. The realized DVR approach returns active power regulation and reactive power compensation during grid fault. Implementation reveals zero voltage ride through and enhanced performance compared to rotor crowbar connection of DFIG.

Venkata Rama Raju R *et al* (2012) introduced the decoupled power control technique for DVR under grid voltage fault with the DFIG based turbine. The control methodology implemented is pertinent to symmetrical components and vector control. The performance of the DVR is regulated by the synchronous PI decoupling controller to obtain decoupled control of voltage during voltage disturbances. The DVR consists of LC filter and three ideal series injection transformer. The voltage to be injected is resolved in to positive and negative sequence component by the positive sequence and negative sequence controller respectively. Multi loop control is assimilated in which voltages are handled at the outer loop and currents at the inner loop correspondingly. Simulations are carried out in MATLAB SIMULINK encompassment. During grid voltage disturbances the designed DVR exclude electromagnetic torque oscillations and stator current unbalance. Thus the generator terminal voltage is sustained constant.

Christian Wessels *et al* (2011) investigated the DVR overcoming the symmetrical and asymmetrical fault in DFIG wind turbine system. Improvement in the fault ride through capability is also observed. In this proposal, the wind turbine is blessed with the uninterruptible fault ride through at sag condition. Compensation of the voltage at the faulty line is attained enabling steady state operation pertaining to the grid code requirements. Comparing to the installation of crowbar the evaluated set up ensures efficient functioning. Tests are conducted referring to the simulation of 2 MW wind turbine and results are reported for asymmetric faults at 22 KW laboratory set up. The featured DVR aids in the protection of the wind turbine which are not furnished with the fault ride through nature. The introduced DVR also secures the distributed load in the micro grid.

Yingdong wei *et al* (2011) introduced a new technique for augmenting the ride through capability of wind turbine generator system. The proposed method is based on the dynamic voltage restorer to the wind generation. The LVRT-DVR is connected in series between the grid and the generator with the help of static switch cabinet. Detailed simulation model is constructed in PSCAD/EMTDC and executed. During fault condition the LVRT-DVR can segregate the wind turbine generators (WTGs) from the voltage dip and maintain the nominal voltage at grid terminals. The wind generator remains connected to the grid at certain times of voltage sag. Anti-voltage technology is employed to proliferate the response speed of LVRT-DVR by enabling the SCRs at ON state in the switch cabinet. Power balance also is achieved between the grid and generator by the braking resistance in the DVR. Results are validated and have proved to be potential. Thus this system facilitates in raised LVRT capability and balanced power flow.

Flannery *et al* (2009) presented the detailed examination and designed a control strategy for DFIG wind turbine with a series grid-side converter for ride-through at unbalanced voltage sag events. The objective of the paper was to characterize the capabilities of a DFIG wind turbine system with series grid side converter (SGSC) during generalized voltage sag events, so DVR was used. So the author has formulated a control structure and dynamic model for unbalanced operating conditions. Experimental results from 2 kW laboratory hardware have been setup to verify an excelling ride-through capacity of the DFIG system under sag conditions.

Alberdi *et al* (2011) focused on the application of a new control scheme to obtain the uninterrupted working of oscillating water column (OWC) based wave-power-generation plants equipped with doubly fed induction generator (DFIG) at the time of balanced grid faults. For this purpose, an airflow valve control and crowbar control has been proposed and coupled to the VFC-controlled DFIG. The growth relies on the execution of a control scheme

that suitably correlates the airflow control, the active crowbar, and the rotor and grid-side converters to permit the plant to endure the service during grid fault. The valve control, based on a modified anti windup PID control law, successfully controls the air valve that adjusts the pressure drop across the turbine to control the acceleration of the turbine. It has been depicted that the formulated control design allows the uninterrupted operation of the wave power generation plant during grid faults, contributing to the fault clearance by increasing the reactive-power production during the voltage dip. Moreover, a significant improvement in machine control during the fault and recovery periods is demonstrated, compared with the uncontrolled case. The simulation outcomes reveal reduction of the rotor currents, improving the transients and staying away from rotor acceleration.

Flores Mendes *et al* (2011) analyzed the behavior of the DFIG during symmetrical voltage sags using models in the frequency domain. A new strategy, the machine magnetizing current control, was proposed in order to enhance the system response during balanced dips. The proposed strategy intends to control the generator magnetizing current in order to increase the damping of the stator flux linkage oscillations, thereby reducing the torque and power pulsation during the sag. The DFIG behavior during symmetrical voltage sags was analyzed through mathematical and simulation results. It was shown that the main problem during balanced sag occurs by the natural response of the stator flux linkage that results in high oscillatory rotor voltages and currents, and subsequently electromagnetic torque and generated power oscillations are developed. This strategy shows improvement in the system response during the sag, but it demands high rotor voltages that depend on the machine operation points that are not feasible for the converter.

Ibrahim *et al* (2011) investigated the application of the dynamic voltage restorer (DVR) to enhance low-voltage ride-through capability of the doubly fed induction generator (DFIG). A control algorithm for the DVR that is dual voltage controllers only was implemented for the two sequence components in the *dq* synchronous reference frame. For effective control of the DVR, digital all pass filters were used for extracting the positive sequence component from the unbalanced grid voltage since they have the advantages of giving a desired phase shift and no magnitude reduction over conventional low or high pass filters. Using the positive sequence component, the phase angles for the positive and negative sequence components of the grid voltage were derived In order to achieve the power rating reduction of the DVR, the stator power reference for the DFIG is reduced during faults. In addition, a control scheme of pitch angle system was applied to stabilize the operation of the wind turbine system in the event of grid faults. PSCAD/EMTDC simulations show the effectiveness of the proposed technique and a feasibility of reducing the power rating of DVR for the fault ride through capability of DFIG.

Ahmad Osman Ibrahim *et al* (2011) modeled the dynamic voltage restorer for the accurate and fault free operation of Doubly Fed Induction Generator(DFIG) wind turbine. They have proposed the usage of digital all pass filters to squeeze out positive sequence component from the unbalanced grid voltage. Thereby phase angles of positive and negative sequence components are obtained. Based on the dq synchronous reference frame a control algorithm is implemented for the components. For stability of the system during faults a control methodology with pitch angle system is applied. Simulations are demonstrated with PSCAD/EMTDC. The MPPT control of wind turbine is locked and decrease of stator power reference is achieved with the designed structure of DVR. This method also avails stable operation at various grid fault conditions. Thus the fault ride through capability is enhanced to a great extent particularly in the DFIG wind turbine systems.

Awad A S A *et al* (2014) compared the application of DVR and STATCOM to improve low voltage ride through (LVRT) capability of wind farms. The proposed work aims to provide recommendations and technical guidelines for the implementation each solution to increase critical clearing time and hence improve the transient stability of SCIG in large wind farms. DVR is modeled in PSCAD using a controlled sinusoidal pulse width modulated (SVPWM) inverter and connected in series to inject certain voltage typically in the range of 0.1p.u, during the fault conditions also the STATCOM was modeled as a controlled reactive current source connected in parallel to the SCIG. Finally DVR provides cheaper solution for LVRT fulfillment compared to STATCOM and also DVR used in central implementation also DVR has proven to enable faster voltage restorations to wind farm generators than STATCOM.

Alan Mullane *et al* (2005) designed a nonlinear controller for power converter based wind turbine generators to enhance LVRT capability. The feedback linearization control technique has been used as a nonlinear controller to maintain current levels within their specified limits during reduced voltage levels under plant model mismatch. The proposed nonlinear controller has been modeled using MATLAB simulink environment and demonstrated a robust enhancement to the WTGs fault ride through performance when compared with the conventional controller design.

Wen Tsan Liu *et al* (2011) targeted on the investigation of the effect of LVRT technologies on the first Taiwan offshore wind farm planning. It began by the examination of the advancement of LVRT technologies, and then focused about the effect of grid strength at the suggested places of

LVRT installation. The critical level of faults that leads to the disconnection of the wind farm from the grid with and without LVRT has been studied. Conclusively, the LVRT characteristic on the transient stability of the power system in Taiwan is determined and the technique for the replacement of LVRT installations with reactive power compensation elements has been proffered. Hence to improve LVRT capability using STATCOM, SVC, and ESS has been used. Finally from the simulation results prove that these additional system components can enhance LVRT in the analyzed offshore wind farm.

Ke Ma *et al* (2014) investigated the loss and thermal performances of a 10 MW three-level neutral-point-clamped (3LNPC) wind power inverter undergoing Low Voltage Ride Through (LVRT) operation. A series of new space vector modulation methods were proposed to reduce the junction temperature in the 3LNPC diode and inner switch, which are the hottest power devices and more equal thermal distribution among the power switching devices. Compared to the normal modulation, the proposed thermal redistributed modulation sequences, which all enable full neutral point potential control ability, can effectively reduce the dwelling time or commutations involving zero voltage level output, achieving more equal thermal distribution and reliving the hottest power devices under extreme LVRT operation of 3L-NPC inverter. It was deduced that, with the projected modulation methods, the thermal distribution in the 3L-NPC wind power inverter undergoing LVRT becomes more equal, and the junction temperature of the most stressed devices can also be freed. The control proficiency of DC-bus neutral point potential, which is the vital consideration for the 3L-NPC converter, is progressed by the proposed modulation methods.

Alepuz *et al* (2013) proposed a control scheme called vector current controller with feed forward of negative sequence grid voltage (VCCF) to fulfill the LVRT requirements in a wind energy generation system based on a permanent magnet synchronous generator connected to the grid with a neutral-point-clamped converter (NPC) back-to-back full power converter. Under grid voltage sag, the generator side controllers and grid-side converters work concomitantly to meet the low voltage ride through requirement by hoarding the surplus active power in the turbine-generator mechanical system inertia while preserving the constant dc link voltage. With this approach, the activation of the dc-link brake chopper could be avoided in some cases. A further study should be enforced to discover in which cases the dc link brake chopper activation could be saved. MATLAB simulation and experimental results substantiates the feasibility of the proposed controller.

Kyung-Min Jin *et al* (2012) examined the DVR controller methods on a stationary and synchronous reference frame for compensating the fault ride through capability of DFIG in a wind energy system. DVR performance vests with the controller in it. Two controllers are dealt in this work including PR(Proportional-Resonant) and PI (Proportional Integral) controllers. PR and Pi controllers are operated and controlled in the stationary frame and synchronous reference frame respectively. The comparisonal view is completed for the transient and steady state responses of the DFIG based WECS. Simulations are perfected with the Psim program for 2 MW DFIG system. Both the controllers have fulfilled responses in the transient and steady state. But the control scheme of PR controller is simpler compared to PI. With this, the DVR operates normally based on the grid codes by augmenting the FRT capacity. It is percepted that DVR with PR controller can be effectively applied to single and three phase systems.

El Hawatt *et al* (2013) constructed a adaptive fuzzy based PI controller to operate the Dynamic Voltage Restorer connected with the DFIG wind turbine for improvement in the low voltage ride through capability. The performance of the DVR is dependent on the controller by which it is operated. DVR functions and operates referring to the fuzzy based PI controller to improve the LVRT capability. When there is a dip in the grid voltage the designed controller is used to return effective results. Self tuning method is indispensible for changes and variations in the parameters and operating conditions. A 2 MW DFIG system is modeled in the MATLAB SIMULINK software platform. The examined system is also compatible with the grid codes to operate in the fault condition. From the result it is reported that the DVR with the novel controller primarily enhances LVRT of the DFIG system.

Zhang *et al* (2012) studied the applications of three single-phase H-bridge dynamic voltage restorer (DVR) with thyristor for switching will be used to improve LVRT capability of DFIG. The advantage was that the circuit and control are relatively independent with voltage and power between three-phase completely decoupled. As a result, there is no need to worry about phase short circuit. The advantage of DVR used in wind farm is that it can easily rebuild wind farm voltage as well as restore AC current of converter rapidly. In addition, the series DVR can adjust reactive power of wind farm quickly and the maximum reactive current it offers won't be affected by voltage drop, which ensures the DVR a good performance in improving LVRT capability of DFIG. Simulation and experimental results show that DVR can support the wind turbine terminal voltage as soon as voltage drops, improving LVRT capability of DFIG.

Shuai Xiao *et al* (2013) proposed a simple flux linkage tracking-based LVRT strategy for the control of rotor side converter (RSC) to suppress the rotor current during grid faults. When the voltage dip was

detected, the flux linkage at the rotor was controlled immediately to identify the reduced fraction of the altering stator flux linkage by the control of RSC, and in this way, the rotor current can be effectively reduced. To prove the proposed control strategy, a case study of a typical 1.5 MW DFIG-based WECS was implemented in simulation using the full order model in MATLAB simulink under Sim Power Systems. In the case study, a comparison with a typical LVRT method anchored on RSC control was given, and the impact of the control parameter on the control performance was also investigated. At last, the validity of the proposed method was verified by laboratory experimentation with a scaled-size DFIG system. Compared with other schemes, the proposed method is very simple to implement, and the fault rotor current can be suppressed effectively with very small torque oscillation.

Shuai Xiao *et al* (2013) presented a method to find out the control limit of RSC under voltage dips. The tool is based on the optimization theory and takes the practical constraints of the RSC into account. To execute the analysis, a simplified DFIG model with decoupled stator and rotor fluxes was presented. The low-voltage ride through (LVRT) problem can be formulated as an optimization problem, which intends to suppress the rotor winding currents with voltage constraints. The Pontryagin's minimum principle (PMP) was employed to solve the optimization problem and the results can identify the control limit of the RSC. The analysis results of the control limit can serve as a guideline to assess the performance of different LVRT methods, to optimize the capacity of the RSC or to determine the activation time of the crowbar for the turbine manufacturers etc. A case study of a typical 1.5 MW DFIG-based WECS was carried out to validate the analytical method quantitatively. By applying the proposed method, the control limit of RSC under various voltage dips can be evaluated and is finally represented by a collection of maximum short circuit current surfaces over the operation area. With the result, the safe operation regions can be readily worked out, thus allowing different LVRT strategies to be designed predictably. Further the proposed method is also verified by experimental tests on a scaled 3 KW DFIG system. The results were expected to help the manufacturers to assess and improve their RSC controllers or LVRT measures.

Surour Alaraifi *et al* (2013) constructed schemes for boosting the voltages in DFIG based wind turbines for improvement in fault ride through capability. The implemented voltage booster schemes comprises of two voltage booster methods which are Dynamic voltage restorer(DVR) and resistive type high temperature superconducting fault current limiter (HTS-FCL) respectively. Both the approaches are designed to operate alternatively and are dealt in the positive and negative reference frames. DVR facilitates the adaptable control for the balanced and unbalanced fault condition. On the other hand HTS-FCL enables quick quenching of voltages at each phases separately. The two strategies also aids in the addition of voltage to the drop and the injection of reactive power. Simulation outputs projects the exceeding performance relevant to grid faults. HTS-FCL has sophisticated boons than DVR which encompasses self-triggering, reduced size, lower cost, and simple construction. DVR can be used for SSR mitigation and power system oscillation damping.

Ahmed abu Hussian *et al* (2014) reported the performance of DVR and Superconductor Fault Current Limiter(SFCL) and made a comparative study for enhancing the fault ride through capability of the squirrel cage induction generator(SCIG). Here, both the DVR and SFCL are made to operate in a WECS including a synchronous generator and a SCIG with double circuit transmission line. The performance of the two were tested in the MATLAB/SIMULINK environment. From the examination of simulation results, it is viewed that both the DVR and SFCL perform well but with certain changes making the DVR better. The main aim of providing better fault ride through capability vests with the DVR. Albeit the control of DVR is complex comparing to SFCL, the cost is lesser. It also has a good speed control capacity with energy storage than SFCL.

N. Amutha *et al* (2012) concentrated on Dynamic voltage restorer for the escalation of fault ride through capability for fixed speed induction generator in the wind generation system. The proposed technique vests with the measurement of critical clearing time(CCT) engaging the approximate steady state model and transient model of SCIG. CCT is same for both the models when the operating slip is high and vice versa for lower operating value of slip. Transient model must be applied for deciding CCT to obtain prompt result because in the approximate model CCTs at higher operating range are similar. DVR is simulated with three control strategies including voltage control, power control and reactance control and it is found that settling time is increased only for power control comparing to other control methods. Thus the increase in fault ride through capability of SCIG relies on CCT. It can be ensued that the power control approach shows predominant enhancement in CCT with DVR than without DVR and other control schemes.

Jelani *et al* (2015) proposed the use of Power Electronic (PE) load interfaces or distributed constant power loads (CPLs) connected to fixed speed SCIG based wind farm for asymmetrical fault ride through (FRT) under asymmetrical grid faults. The proposed system configuration provides an alternative to the conventional STATCOM and DFIG wind turbine by effectively controlling the installed resources at the distribution level. In addition to the

typical positive sequence reactive current injection, the proposed method suggests a negative sequence active and reactive current injection during the FRT operation to mitigate the voltage unbalances without exceeding the peak current limit of the PE load interface. It has also been observed that the compensation of negative sequence voltage improves the performance of SCIG by eliminating the torque ripples. The compensation of positive sequence voltage avoids a possible voltage collapse at the low voltage distribution level and improves the reliability and stability of the wind farm. A detailed simulation analysis is carried out to understand the voltage control performed by distributed CPLs and the resulting operation of the SCIG under unbalanced grid fault. Centralized compensation of the asymmetrical grid fault by a STATCOM is compared with the distributed compensation by CPLs. The results suggest that each individual CPL injects lower current for maximum FRT enhancement compared to a dedicated STATCOM.

Hossain *et al* (2012) designed and implemented a new control scheme for reactive power compensation, voltage regulation and transient stability enhancement for wind turbines equipped with fixed-speed induction generators (IGs) in large interconnected power systems to improve low voltage ride through (LVRT) capability by extending the range of the operation of the controlled system to include typical post-fault conditions. A systematic procedure was proposed to design decentralized multi-variable controllers for large interconnected power systems using the linear quadratic (LQ) output feedback control design method and the controller design procedure was formulated as an optimization problem involving rank constrained linear matrix inequality (LMI). A ten-machine power system has been used to evaluate the performance of the designed controller. Simulation results shows that even the non-linear interconnections between different types of generators and significant operating condition variations following the fault occurs, the proposed controller can greatly enhance the transient and voltage stability as well as LVRT capability of wind turbines. Finally, it is shown that a static synchronous compensator (STATCOM) with energy storage system (ESS), controlled via robust control technique, is an effective device for improving the LVRT capability of fixed-speed wind turbines. The future perspective of this work is to design reduced order controllers for distributed systems.

Karthigeyan P *et al* (2014) have been compared the performance of Dynamic Voltage Restorer (DVR) and static Synchronous Series Compensator (SSSC) in a wind turbine system fed through Fixed Speed Induction Generator (FSIG) under Asymmetric faults. Here the proposed system has been evaluated and simulated using MATLAB simulink environment also the controllers used in this paper was vector control direct quadrature axis reference frame fed hysteresis control using dual second order generalized integrator phase locked loop (DSOGI-PLL). To mitigate faults DVR was connected in series with the wind turbine fed FSIG to compensate positive, negative sequence voltage and current while maintaining power quality in the overall system and the same was repeated for SSSC. From the THD reduction results that clearly indicates the performance of DVR was better than the SSSC.

H.Gazatananga *et al* (2007) investigated the DVR in the fixed speed induction type wind farm to accomplish the interconnection requirements. The dynamic voltage restorer (DVR) is dealt based on Hybrid real time tests i.e a prototype. The DVR facilitates the effective functioning of the wind farm in transient mode of operation. The vital role of DVR is to govern active power generated in the wind farm and its transfer to the grid for distribution. In this paper the DVR actively participates in the supply and export of active power to the grid particularly during fault condition. At normal operating condition there exists only a limited participation of the developed DVR device. The transient behavior of the WECS is regulated by minimum voltage compensation (MVC) method. A real time prototype model is implemented under reduced-scale testing conditions and offline simulations are carried out and executed in PSCAD. The real time implementation is done with reduced cost and it curtails the process of testing.

Dionisio Ramirez *et al* (2011) examined the wind generators pertaining to the dynamic voltage restorers for improvement in the low voltage ride through capability. The authors have evaluated the control scheme with two-step approach in the DVR for squirrel cage induction generators. First is the compensation of the voltage dip along with phasor in series with the grid voltage phasor. Second is the injection of the reactive power to the grid by rotating the series voltage. On comparison with other control scheme DVR extends its support to the recovery of voltage by controlling the reactive power thereby satisfying new grid codes. The focused control scheme is experimentally tested in the laboratory. Thus the squirrel cage asynchronous generator with the DVR remains intact with the grid at times of the voltage disturbances particularly voltage sag.

Teng Long *et al* (2013) analyzed the comportment of the brushless doubly fed induction generator (BDFIG) under asymmetrical low voltage faults in cases of the phase to phase, phase to ground, and phase to phase to ground short circuits. Analysis shows that the major issue for an asymmetrical low voltage fault is from the zero sequence of the control winding (CW) current but not the backward sequence current. The severity of these three types of asymmetrical faults has been compared. Also introduced a practical control scheme for the BDFIG to ride through asymmetrical LVRT without any extra hardware such as crowbars. The proposed

control strategies are experimentally verified by a 250 kW BDFIG. The control algorithm was implemented in MATLAB Simulink in an xPC Target computer which receives all the measurements and generates PWM signals for the machine-side converter. The sampling time of the control loop was 0.5 ms. The BDFIG based wind turbine with the proposed control scheme is able to show high stability and a low cost of grid integration.

Teng Long *et al* (2012) analyzed the behavior of the brushless doubly fed induction generator (BDFIG) under symmetrical low voltage faults. Also introduced a practical control scheme for the BDFIG to ride through symmetrical LVRT without any extra hardware such as crowbars. The proposed control strategies are experimentally verified by a 250 kW BDFIG. The BDFIG based wind turbine with the proposed control scheme is able to show high stability and a low cost of grid integration.

Mahalakshmi *et al* (2013) presented the simulation of DVR with pulse width modulation (PWM) based controller using Matlab/Simulink. The performance of the DVR depends on the efficiency of the control technique involved in switching the inverter and the DC energy storage system. The two control techniques such as Proportional Integral Controller (PI) and Sliding Mode Controller (SMC) were used. The DC energy storage system composed of DC link capacitor supported by Permanent Magnet Synchronous Generator (PMSG) based Wind energy conversion system was applied. Simulation shows that both PI and SMC techniques give identical results regarding the voltage compensation at the load side, but the response was faster for SMC. Nevertheless, SMC algorithm was simpler for digital implementation thus it can be preferred in practical power system applications.

Ki-Hong Kim *et al* (2012) proposed a low-voltage ride-through scheme for the permanent magnet synchronous generator (PMSG) wind power system at the grid voltage sag. A new voltage controller with dc-link has been designed and executed using feedback linearization theory by pondering the nonlinear relation between the generator speed $\omega m$ and the dc-link voltage $V_{dc}$. The GSC controls the grid power according to the MPPT strategy. For unbalanced grid voltage conditions, the current control using a double-frame controller has been applied for the positive and negative-sequence components. The control algorithm has been validated and verified by PSIM. Simulation is accomplished for a 2 MW PMSG wind power system. Also, experimental verification has been done for a 2.68 kW PMSG wind turbine simulator. The results have shown a better dc-link voltage control performances for unbalanced grid voltage sags.

El Moursi *et al* (2013) presented a novel control design for improving the performance of large-scale wind park (LSWP) based on self-excited induction generator under unbalanced voltage conditions. A dual controller for static synchronous compensator (STATCOM) employing controller by employing positive and negative sequence synchronous frames was implemented and analyzed in response to severely unbalanced voltage conditions. The test system simulated represents a wind park rated at 100 MW connected to a weak electrical grid. The potential of the dual STATCOM controller is evaluated and analyzed for severely unbalanced voltage conditions at the grid interface of LSWP. The dual controller with STATCOM overloading capability was tested and compared with the performance of the positive sequence controller in response to different types of asymmetrical grid faults at low short-circuit ratios. The simulations performed using PSCAD/EMTDC demonstrate superior performance of dual STATCOM control strategy for improving unbalanced operation, fault ride through capability and transient stability margin in response to severely unbalanced voltage conditions. The STATCOM dual controller significantly minimizes voltage dip and ensures better damping of the generator speed.

Mahfouz *et al* (2013) analyzed the implementation of three-level inverter based on a static synchronous compensator (STATCOM) for the improvement of the ride-through and stability of fixed speed wind farms. Vector current control is used as robust control to inject the required reactive power from STATCOM. This study also emphasizes the analysis of torque speed curve to evaluate the induction generator speed limit and for defining the critical clearing time of the fault according to the selected STATCOM rating. MATLAB simulation results under fault conditions were performed to validate the enhancement of wind farm low-voltage ride-through capability and increasing the critical clearing time by installing STATCOM.

Andres.E.Leon *et al* (2011) enunciated the capability of DVR operating under unbalanced conditions in a grid connected WECS. The merit of completely excluding the negative sequence current and making the negative sequence voltage zero thereby preventing overheating, performance loss, reduction in generator life along with the avoidance of 2ω pulsation in mechanical torque, stress in gear box respectively. The amiable character of their DVR control approach to operate and function with static var compensator is also mentioned. Their overture is an alternative for SCIG based WECS entirely varied from the conventional method of using the STATCOM alone. The idea presented by them is centered to install DVR along with STATCOM. Thereby fulfilling the grid code requirements, increase in the LVRT capability and bearing the short circuit of larger duration. They have also mentioned the advantages of STATCOM and DVR of meeting the current demanding standards and isolation of the wind farms from negative

sequence voltages at a single inculcation. They have further represented the better performance of wind farm during unbalanced conditions and conducted many tests with the DVR control method which proves to be tempting approach and solution to work with the wind energy conversion system albeit increase in the requirements grid code.

Arulampalam A *et al* (2006) introduced the STATCOM endowed with battery energy storage (BES) installation in the wind farm for enhancement in the power quality and stability of the system. A very new mixed STATCOM-BES control strategy is modeled with the braking resistor (BR) in BES and hence called hybrid. During network faults at transient overload capability, the redundant power is to be absorbed by the STATCOM. This leads to incorrect rating of the STATCOM. The main theme of implementation is to improve stability and power quality of the fixed speed induction generator in the wind turbine. Simulations are executed in a time-stepping transient software package. STATCOM-BES system dismisses fluctuations in the power and eradicates the absorption of reactive power providing quality power. It also assists in the reactive power injection fetching stability to the system for about 300% and additional 50% with BR. Economic conditions needs to be favoured for real time installation.

Aboul-Seoud T *et al* (2009) and A.M.Sharaf presented a compensation strategy in a wind energy conversion system with dynamic voltage regulator(DVR) for a standalone remote area system. The projected method is the FACTS based DVR which is governed by a tri-loop dynamic error-driven PI controller. Pulse width modulation (PWM) technique is used to give signals and regulate the controller. The methodology can be used in a rural area fetched with squirrel cage induction generator (SCIG) at the separately excited mode for ameliorating the power quality. The designed topology is executed in simulation with decreased total harmonic distortion in load currents. The simulated output is interpreted with and without DVR. An important asset of the work comparing to other methods is the improvement in power factor of the network to which it is connected. It also facilitates in the stabilization of voltage, reduction in the supply current and alleviation of losses in the distribution feeders. The developed scheme is robust and cheap.

Sugirtha M G *et al* (2011) focused on the power quality issues in wind energy power system connected to grid. They have concentrated on the Dynamic voltage restorer injecting voltage in to the grid connected wind plant to improve the power factor and minimize the losses. IEC-61400(International Electro-technical Commission) standards are applied to measure the performance of the wind turbine. Normally in a WECS comprising induction type of generators, absorb reactive power from the grid. Dynamic compensation is performed by the DVR. Here tri-loop dynamic error-driven PI controller is used. Its output is considered as the reference signal of the PWM. Simulations are executed using MATLAB/SIMULINK. Power System is designed using SIM-POWER tool box. It effectively enables the exchange of reactive power between the grid and generators. The dynamic property of wind leads to non-linearity of the output power causing power quality issues in the WECS. Thus by introducing DVR to the system leads to voltage stabilization with the reduction in losses of the feeders.

Farsadi M *et al* (2013) designed a new control scheme of DVR for enhancing the operation of the wind farm by using fuzzy logic controller. Alternative energy source for DVR is from photovoltaic (PV) system. The proposed system here is the DVR coordinated by fuzzy logic controller (FLC). During fault condition power quality issues such as voltage sag and swell emerges in the network. The developed FLC based DVR detects the fault and clears it quickly. A dynamic method of combining the FL and carrier modulated PWM inverter is introduced. A simulation for a 12-pulse DVR using PV is developed in MATLAB SIMULINK software. The DVR also aids in maintaining the terminal voltage constant in spite of instability due to fault condition. The wind farm remain connected to the system and remains stable by compensating voltage sag and swell. Utilizing PV as the alternate source for DVR represents the importance given to renewable energy sources.

Xuanxuan Liu *et al* (2007) investigated the influence of placing the distributed generation (DG) on distribution system using DVR to compensate the distortion of voltage. In DVR semi period algorithm was used to take out the fundamental positive sequence voltage by decomposing instantaneous link to solve the quantity required for voltage compensation by direct detection algorithm. MATLAB simulations have been done to test the efficacy of the DVR and the results proved a good guarantee for regulation of voltage and for maintaining the voltage quality for sensitive loads.

David Santos Martin *et al* (2009) analyzed the consequence of unbalanced voltage over doubly fed induction generators (DFIGs) and proposed a contemporary control strategy, called dynamic programming power control plus (DPPC+), based on dynamic programming control. To certify the feasibility of the proposed method with DPPC+, an experimental test has been represented on a 20 kW test bench, consisting of a DFIG and induction motor drive. It is ensued that the DPPC+ is suitable for acquiring a good dynamic response with the current distortion control and power and/or torque oscillations control for both steady state conditions and at voltage dip conditions to augment low-voltage ride-through capability. The working of proposed

DPPC+ when applied to the rotor converter to maintain the injected stator power in the grid constant. The proposed algorithm DPPC+ is thus capable of controlling the decoupled active and reactive power of DFIGs, under unbalanced grid voltage conditions, as it has been expounded by the experimental results. Also DPPC+ is also a very robust control system for a wide range of unbalance factor values with high dynamics at nearly constant commutation frequencies. Hence all these factors make DPPC+ an attractive proposition that ensures a high-performance control of drives for DFIG generators, among other types of generators used in wind energy applications.

Jingya Dai *et al* (2011) developed a new control scheme for a current source converter (CSC) based WECS to ride through grid faults without external braking resistors or energy storage components. A unified dc-link current controller associated with both generator and grid side converters have been employed to maintain the dc-link current well within limit and support grid-voltage recovery. The coordinated control of the input and output power can also be utilized to smooth power output while maintaining fast control response of the dc-link current. Simulation and experimental results have been proved to verify the proposed control scheme.

Matias Diaz *et al* (2014) designed and tested a new 3-phase 4-leg matrix converter-based voltage sag/swell generator (VSG) to test WECS under grid-voltage-sag conditions was described. The proposed matrix converter (MC) based VSG, as an alternative to the back-to-back converter, and no complex modulation algorithms were required. Moreover, the MC is a bidirectional converter and no dissipation of energy in passive loads is required when this VSG is used. A 3 kVA 3-phase 4-wire MC-based VSG prototype is implemented. To compare results, a 3 kVA transformer-based VSG and a commercial programmable AC Power source are also presented. Therefore the proposed VSG has a very simple design and control and is suitable for most research and development tests to evaluate the behavior of WECS under voltage-sag conditions. Hence this VSG can be used to generate the symmetrical and asymmetrical faults required to test LVRT algorithms in a laboratory environment.

Abolhassani *et al* (2008) developed a simple and low-cost variable speed integrated doubly fed electric alternator/active filter (IDEA) for wind energy conversion systems. The proposed IDEA is capable of simultaneously capturing maximum power of wind energy with fluctuating wind speed and improving power quality by canceling the most significant and troublesome harmonics of the utility grid. The back-to-back current-regulated power converters were employed to excite the rotor of IDEA. The control strategy of rotor side power converter is based on position sensorless field oriented control method with higher power density. A laboratory prototype has been fabricated and tested, with TMS3202407 DSP-based controller to control the back-to-back power converters. The proposed system can be adopted for large- and mega-scale grid-connected wind turbine. The use of this system can eliminate the need for grid-side active filter.

Zhang *et al* (2010) reported a statistics-based analysis method for assessing the impact on voltage quality caused by wind power generation. Voltage deviation has been computed using the probabilistic models of wind power production and grid Thevenin impedance. An index called significance level of the voltage deviation $\alpha$ has been developed to provide a probabilistic measure of the voltage quality performance. By considering the contributing factor from each of the grid states that constitute $\alpha$, possible solution methods to improve on voltage quality can be obtained. This will lead to a corresponding increase in the wind power penetration level that can be accommodated in the grid, with acceptable voltage quality at the PCC.

Hua Geng *et al* (2011) presented an improved direct voltage control (DVC) strategy for the control of terminal voltage and frequency of a standalone wind driven self excited induction generator with variable loads. The DVC strategy, including a proportional-integral (PI) regulator, lead–lag corrector, and a feed-forward compensator, was designed based on the system transfer function matrix. The PI regulator can eliminate the steady-state tracking errors of the terminal voltage. The lead–lag corrector was employed to enlarge the phase stability margin of the dominant loops while the feed forward compensator was adopted to mitigate the voltage harmonics resulting from the cross-coupling dynamics. The simulation and experimental results verify that the proposed strategy has a fast dynamic response and can effectively control the generated voltage with low harmonic distortions under different linear or nonlinear loads.

Cheng *et al* (2012) developed a calibration test platform of commercial PQ instruments for wind energy system. Autoregressive (AR) based synchronization technique possesses the analysis capability with high-frequency resolution, and all the PQ analysis can be precisely performed. The estimation errors from squaring multiplier of the IEC flicker meter can be prevented with the proposed voltage envelope extraction technique. To guarantee the accuracy of estimation, some features are considered in the proposed system as follows. The sampling frequency can be synchronized with the power-system frequency according to the recommendation of the IEC Std. 61000-4-7. The voltage envelope of flicker can be accurately extracted without the errors due to squaring multiplier in the IEC Std. 61000-4-15. The detection and characterization of voltage drops cannot be affected by the power-system frequency deviation. In

addition, the analysis algorithms can be easily modified according to the latest revisions of international standards without taking hardware requirements into account.

Moataz Ammar *et al* (2014) presented a super capacitor energy storage system (ESS) as a solution to the voltage flicker problem in weak distribution networks resulting from Wind power (WP) integration. A filtering based control algorithm was shown effective in both alleviating the WP flicker severity and properly managing the ESS state of charge (SOC). The ESS was found to have a superior flicker mitigation capability to that of the reactive power control approaches. The proposed power sizing of the ESS is defined by the estimated turbulence intensity and wind speed average at the installation site. A 2 MW wind generator of the doubly fed induction generator type was employed as a source of WP and simulations were conducted on a simplified test system, as well as a detailed 25 kV distribution network on which results were compared with acknowledged reactive power flicker mitigation approaches and verified by prototyping in a real-time simulation platform. The flicker measurement procedure was conducted per IEC Standard 61000-4-15.

Li *et al* (2014) designed a control system for a three-level hierarchical structure for wind–battery energy storage hybrid power system. The primary control level was the grid demand calculating level which processes the grid demand. The secondary control level was energy management level and it calculates the output capability of active and reactive power according to present state of the batteries and converters. And the third control level was the VSC control level which ensures that the BESS power output matches the instruction given by the secondary control level. The advantage of the control strategy was that the state of charge of a battery energy storage system was regulated within proper range and the voltage at the point of common coupling was kept stable while smoothing wind power. Effectiveness of the proposed method is validated by MATLAB/SIMULINK simulations and experiments.

***Conclusion:***

This paper has made a wide overture of using the Dynamic Voltage Restorer for the grid connected wind energy conversion system. Comparison of results with DVR and with the devices including STATCOM, SSSC and UPQC has been provided. Doubly fed induction generator based wind energy conversion system provides efficient power generation in spite of the fault conditions as symmetrical and asymmetrical faults with DVR. The faults may be of any type including the single phase fault, double phase fault and three phase fault. The DVR with DFIG is explained in (Peng Cheng, 2012; Venkata Rama Raju, 2012; Christian Wessels, 2011; Yingdong Wei, 2011; Patrick, 2009; Mikel Alberdi, 2011; Victor Flores Mendes, 2011). A profound survey reveals that DVR installation with the existing grid systems would also aid in the enhancement of the low voltage ride through capability (Ibrahim 2007; Andres, 2011). The performance of the power system vests with DVR operation and the type of generator connected to it. The fault ride through capability is with the DVR without noticing the generator type is presented in (Ibrahim 2007; Surour Alaraifi, 2013).

DFIG based wind energy systems with many control methodologies and features are proposed. The comparison of controllers as PI and PR with braking resistors is also given. Many real time and experimental verifications have been conducted and validated in (Ibrahim 2007; Surour Alaraifi, 2013). For fixed speed applications SCIG has been used and their implementations proved effective in (24)-(30).The incorporation of DVR with BDFIG based on different control algorithms are addressed in (Teng Long, 2013; Teng Long, 2013).

The low voltage ride through capability is improved in permanent magnet synchronous generator with the wind energy systems (Mahalakshmi, 2013; Ki-Hong Kim, 2012). STATCOM implementations in the wind farms have been reported. Many authors also have compared the performances but the performance of DVR has been proved efficient. (Mohamed El Moursi, 2013; Andres, 2011). Comparisons of different controllers are also exhibited and results are validated with the experimental set up. Diverse control methodologies as tri loop dynamic error control, fuzzy logic, semi period algorithm, dynamic programming power control plus(DPPC+), dc link current controller,3-phase 4-leg converter are addressed (Sugirtha, 2011; Matías Díaz, 2014). Different control strategies as integrated doubly fed electric alternator/active filter (IDEA), choosing significance level of the voltage deviation $\alpha$,employment of lead–lag corrector with feed-forward compensator, autoregressive synchronization technique are reported in (Mehdi Abolhassani, 2008; Moataz Ammar 2014). Battery energy storage systems as three-level hierarchical structure for wind–battery hybrid system have also been designed and incorporated in the power system (Kai, 2014).

Simulation tools such as MATLAB, PSCAD and EMTDC are commonly used to analyze the operation ability. DVR can also be controlled and governed by soft computing techniques like Fuzzy logic controller, Neural Networks, Neuro fuzzy controller, Neural network tuned fuzzy logic controller and ANFIS. Optimization techniques such as Differential Evolution, Genetic Algorithm, and Particle Swarm Optimization can also be implemented. Power quality based issues are rectified predominantly in DVR rather than other devices.

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