Power Quality Improvement of Grid Connected Wind Farms through Voltage Restoration Using Dynamic Voltage Restorer

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Abstract- Increasing sensitivity of the loads with respect to power quality has gained the interest of power system analysis and power quality improvement techniques. The voltage sags or swells which are characterized by rms voltage variations outside the normal operating range of voltages due to faults may lead to improper disconnection of wind turbines. This paper deals with the effective voltage sag/swell mitigation using Dynamic Voltage Restorer (DVR), to regulate the terminal voltage of the wind farm. The DVR utilizes a feed forward vector control based algorithm to generate the PWM based firing signals for injecting appropriate compensation voltages. The actual wind farm field data of the voltage sag and swell events during fault conditions are re- created using MATLAB/Simulink and restored by employing the DVR. The simulation results are shown to verify the operation of DVR during balanced voltage sag and swell conditions.

Keywords Dynamic Voltage Restorer (DVR), Voltage sag, Voltage swell, Feed forward vector control, Fault Ride Through Capability.

1. Introduction

There is an increasing need for study of power quality issues in wind farms due to the steady growth of wind power integration to grid. It mainly affects the reliability and dynamic stability of power system due to the following reasons: (a). The difference in behavior of wind plants compared to the conventional generation system and (b). Most of the wind farms in India are connected to weak grids due to rural area installations. Thus, wind farms connected to weak grids lack the capacity to handle high penetrations. Therefore, more dynamic analysis and study on power quality issues are required. The various power quality issues which can be noted in connection to wind farms are shown in Figure. 1.

Wind Power Plants (WPP) will stop operating during abnormal conditions to avoid further voltage collapse [1]. Due to increasing capacities of wind farms and large single WPPs being connected to the grid, new grid codes have been laid to ensure the system stability and reliability. Thus, Fault Ride Through (FRT) capability requirements of wind farms in India necessitate efficient ride through of voltage sag/swells. During the occurrence of a grid fault, the grid codes prescribe that the wind turbines must stay connected to the grid and support it by generating reactive power to restore the grid voltage quickly after the fault [2].

Voltage sags and swells are the major power quality issues, generally associated with system faults. These faults include Single Line to Ground faults (SLG), Double Line to Ground faults (DLG) and Short- Circuit faults or tripping [3-5]. A voltage swell can happen due to switching off a large load, energizing a large capacitor bank or on unfaulted phases during a SLG fault. The Low Voltage Ride Through (LVRT) capability of WPPs requires the wind turbines to remain connected to the grid for a specific period of time during grid voltage sag conditions [6]. The High Voltage Ride Through (HVRT) capability requires the wind turbines to remain connected during voltage swell as prescribed by the grid codes [7].

Therefore, the Dynamic Voltage Restorer (DVR) attempts to ride through voltage sag/swell conditions during faults to prevent WPPs from unwanted tripping and to enhance the FRT capability. The compensation capability of a DVR depends on its maximum voltage injection ability and the amount of stored energy available. The compensating voltages are measured appropriately by the controller and injected using injection transformer. The compensating voltages are drawn from a temporary supply/ storage unit. The DVR also attributes to lower cost, smaller size, and fast dynamic response to disturbances [8].

The objective of the paper is to simulate a DVR based voltage sag/swell mitigation technique with dc-link capacitor energy storage using feed forward based compensation. This paper presents a feed-forward vector control based modeling, analysis and simulation of DVR using MATLAB/Simulink with performance comparison during fault occurrences as per field data. The same sag/swell amplitude and duration in the field data are used for simulation. The field data recorded at the Chinnaputhur Substation for 40 days at Dharapuram district in Tamil Nadu of India is used for the study. Totally 22 events have occurred during the study period, of which 6 are sag events, 1 swell event and remaining are interruptions [9]. By incorporating the same duration,the reliability of the DVR compensation technique during the corresponding symmetrical and unsymmetrical fault conditions can be ensured.

The paper has the following sections: Section 2 describes the principle of DVR operation; Section 3 includes the circuit and control strategy description of the DVR and Section 4 includes the simulated results with field data. Finally, Section 5 concludes the paper with observation and remarks.

2. Principle of Operation of DVR

Dynamic Voltage Restorer (DVR) consists of a voltage source converter, a LC based line filter, coupling transformer connected in series with the grid to correct the voltage disturbances during faulty grid conditions [10]. It protects the sensitive loads during the voltage sag/swell conditions by injecting the corresponding compensating voltages through the transformer. The phasor diagram of a voltage sag event correction through In-phase voltage injection scheme is shown in Figure. 2.

The dynamic voltage restorer injects a dynamically controlled voltage in series based on the widely used In-phase compensation scheme to the bus voltage by means of a coupling transformer for voltage restoration and regulation [11]. The amplitude of the injected phase voltage is controlled to avoid any power quality disturbance of the loads connected to the same feeder.

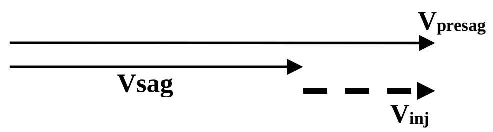

Figure. 2 Phasor diagram of the In-phase voltage injection scheme in DVR

The DVR injects a voltage V_{inj} such that the load voltage V_{sag} remains at V_{presag} both in magnitude and phase angle. Figure. 3 shows the principle of operation of DVR.

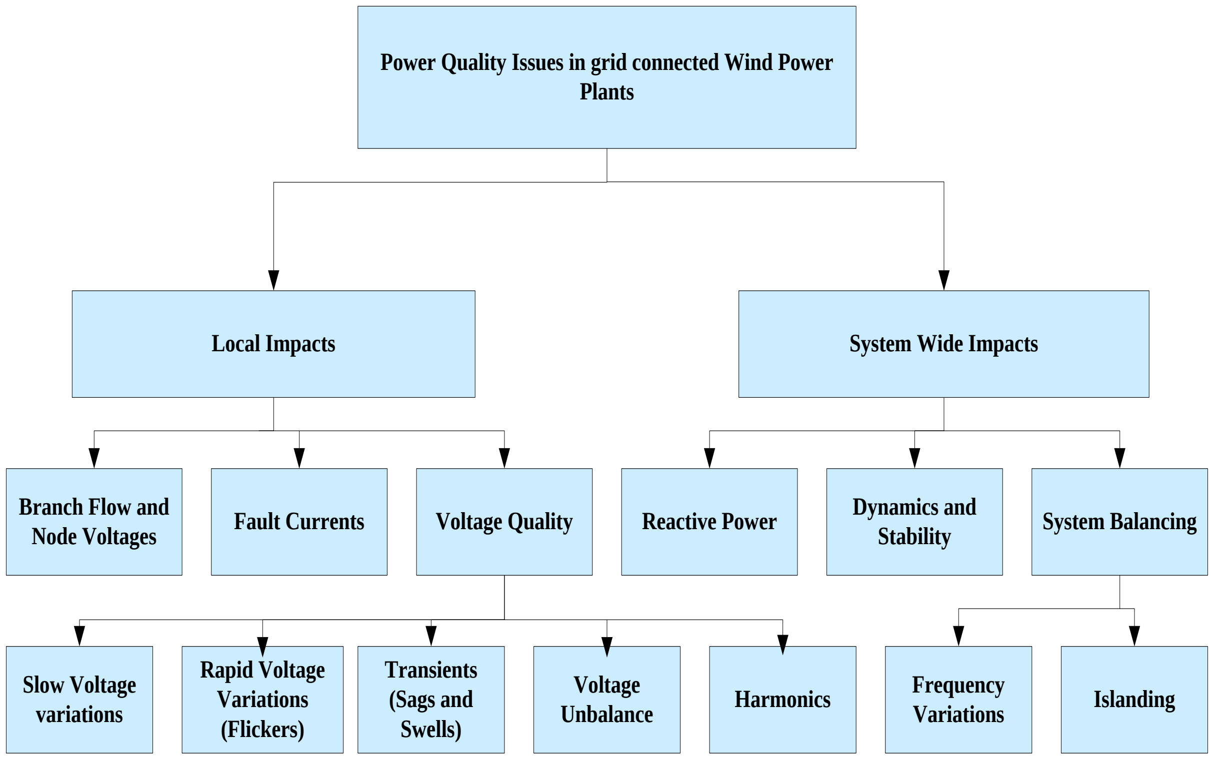

Figure. 1 Various Power Quality Issues in Wind Farms.

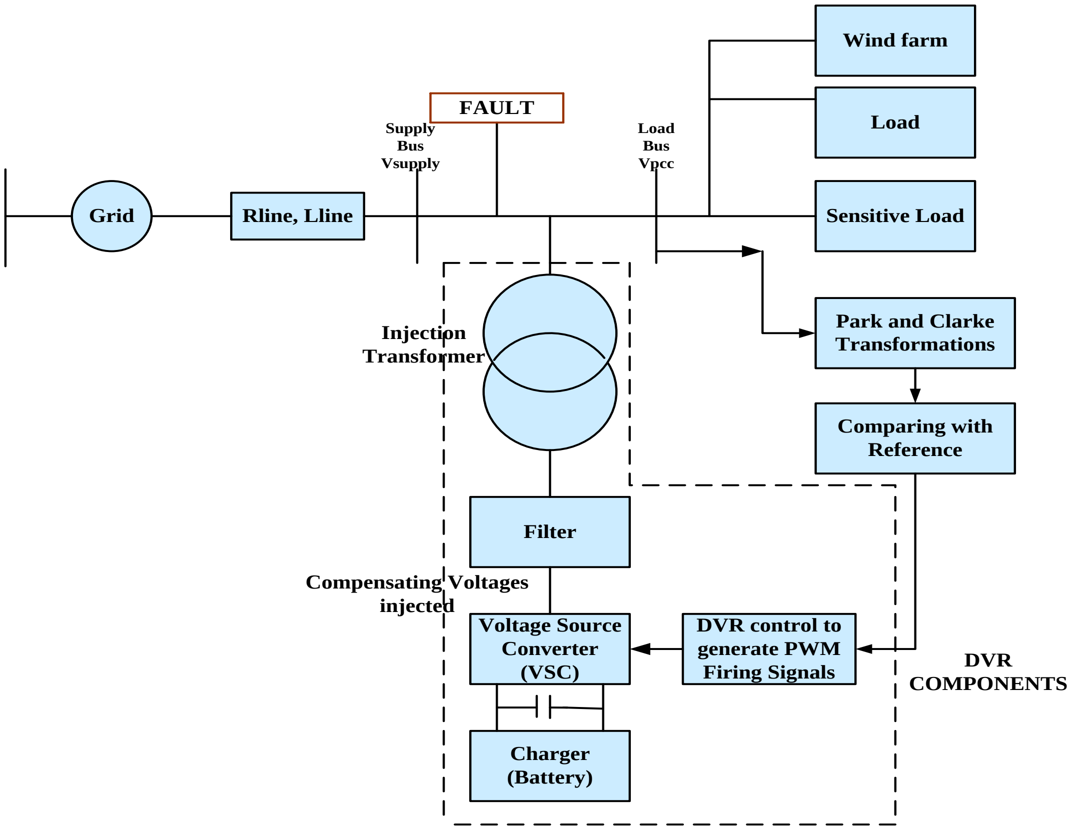

Figure. 3 The principle of operation of DVR

3.Control strategy of Dynamic Voltage Restorer

3.1.Circuit Description of DVR

The DVR includes a voltage source converter connected through a passive LC filter and a dump resistor R to the injection transformer. The voltage source converter injects the appropriate voltages based on the PWM based firing pulses generated through the control method [12]. The external voltage is drawn from the battery based energy storage. The filtered voltages are injected to the grid through a three- phase series transformer with a turns ratio of 1:1.

The feed forward based compensator attenuates the oscillation of the output voltages thereby neglecting overshoots during abrupt changes in the output voltage [19]. Using feed back control may avoid including the voltage drop across transformer and passive filter and also the switching losses but has the disadvantage of an additional delay [20]. Hence, this control is used to ensure the fast dynamic response during fault conditions.

$$V_{L,k(t)} = V_{G,k(t)} + V_{inj,k(t)} \tag{1}$$

In Eq. 1, the voltage suffixes V_L, V_G and V_{inj} denotes the line, grid and injected voltage quantities respectively. Also, k denotes the number of phases. Sinusoidal waveforms of these voltages are given in Eq. 2 [16,17].

$$\left.\begin{aligned} V_{L,k(t)} &= V_{Lm,k}\sin\left(\omega t-(k-1)*120^\circ\right) \\ V_{G,k(t)} &= V_{Gm,k}\sin\left(\omega t-(k-1)*120^\circ\right) \\ V_{inj,k(t)} &= V_{injm,k}\sin\left(\omega t+\phi_k-(k-1)*120^\circ\right) \end{aligned}\right\} \tag{2}$$

Where k=1,2,3.

V_{Lm} - peak values of load,

V_{Gm} - peak values of grid,

V_{injm} - peak values of injected voltage,

ϕ - phase angle of injected voltage

$$\text{Where } \phi = \begin{cases} 0 \\ 180 \end{cases} \tag{3}$$

The phase angle can be varied between 0 to 180 degrees based on the specific compensation technique of a DVR as shown in Eq. 3 [16,17]. Since, we have incorporated in-phase compensation technique here the phase angle is 0. The system parameters included in the simulation are given in Table. 1. A dc link voltage source is used for energy storage and in order to avoid voltage unbalance during fault conditions, a capacitor has to be added to the system. The capacitor has to be sized slightly higher in order to avoid any variable voltages[18].

Table. 1 Simulation parameters

S.No	System Parameters	Values
1.	Supply voltage from grid, Vrms	380 V
2.	Grid frequency	50 Hz
3.	Line impedance	0.5 mH, 0.05 Ω
4.	Injection transformer with turns ratio	1:1
5.	Filter inductance	5 mH
6.	Filter capacitance	50 μF
7.	Load resistance	60 Ω
8.	Load inductance	0.15 mH
9.	dc-link voltage V_{dc} and Capacitance C_{dc}	700 V, 3000 μF

3.2.Description of the control strategy used

The feed-forward based vector control is used to generate the appropriate PWM based firing signals. These signals generate the compensation voltages through the voltage source converter. Thus, the injection voltages generated are injected through the series transformer. Therefore, by mitigating the voltage sags, the low voltage ride through of the fault is made possible. Thereby, overcoming the fault conditions to prevent the unwanted tripping of wind farm and to protect stable grid operation. The rotating dq frame with feed forward compensation has been used for the control of DVR [13,14].

The DVR consists of a Phase Locked Loop (PLL) for synchronization with the grid supply [15]. Relatively slow PLL helps to minimize the phase jump problems between pre-sag and post sag phase values [14, 15]. Therefore, identification of sag freezes the PLL and takes only the post sag voltage phase angle. The reference signals V_{dq} is compared with the load voltages and the V_{inj} is generated.

4.Simulation Results

The simulation results of the DVR compensation are compared with field data taken at Chinnaputhur substation. Totally 6 sag events and 1 swell event occurred in the field at the particular time of study. The simulation results are compared with field data for a instantaneous and a momentary sag and one swell condition. The MATLAB/Simulink based DVR circuit consisting of the grid connected to RL line impedance, an injection transformer, a non linear load and the control circuit. The control strategy includes the PLL, Park and Clarke transformations and the PWM signal generator.

The fault events are taken from the substation at Chinnaputhur which was constructed and commissioned in 2008 by Enercon Pvt. Ltd, located at Dharapuram District of Tamil Nadu in India. It has totally 14 wind farms with 148 wind turbines with a total capacity of 123 MW connected to a 22 kV bus bar. The wind turbines installed in this wind farm are variable speed Permanent Magnet Synchronous Generator (PMSG) based turbines.

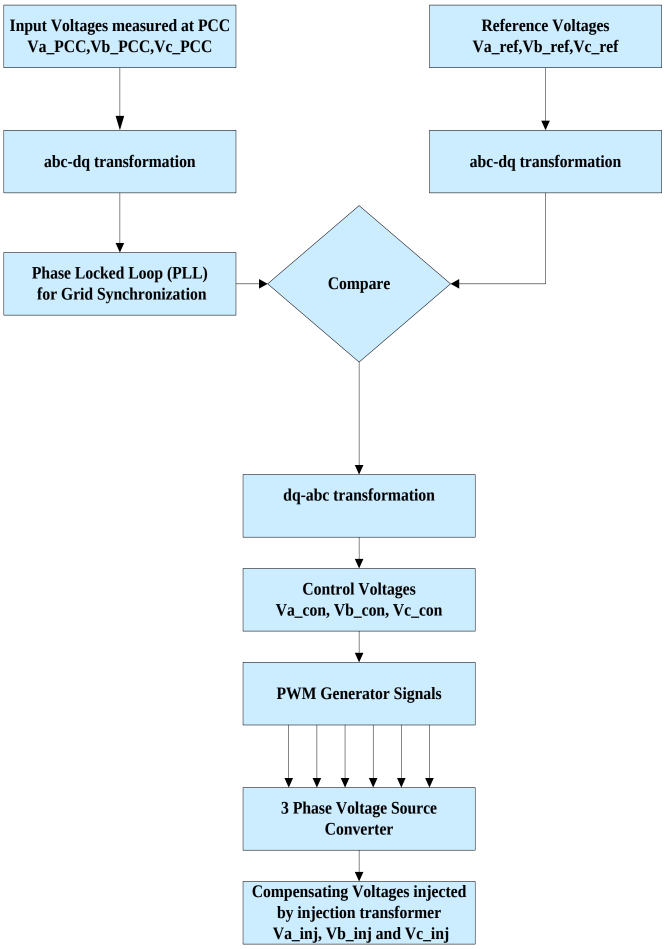

Figure. 4 Feed forward based compensation of DVR control

Each turbine is capable of generating 0.85 MW at 0.44 kV and connected to a transformer of rating 0.950 MVA, 0.44 kV/22 kV. Two power quality analyzers namely Fluke 435 and Dranetz were installed in the substation during the period of study for 40 days. The Power Quality events as per the EN50160 standard are said to be recorded.

The occurrences of sag were noted due to varying power demand and fault in substation and swell due to removal of load at the distribution level. Transients occur due to switching of capacitor banks or isolators and cannot be restored using a DVR. The sag and swell events occurring in this substation connected to wind farms are used for comparison [3].

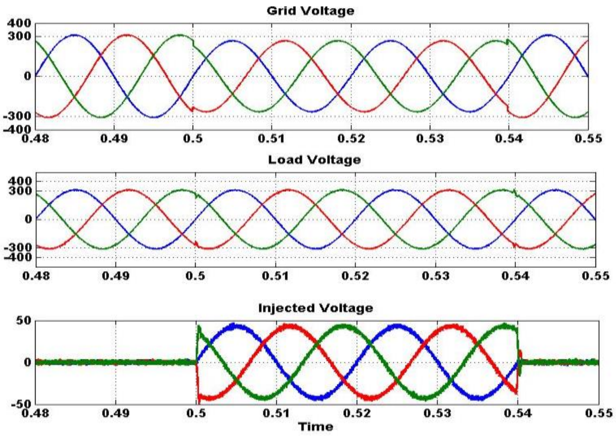

Figure. 5 (a) the amplitude of Grid voltage, Load voltage and the injected voltage for balanced voltage sag up to 0.76 pu (between 0.5 to 0.54 sec) for 0.0398 sec

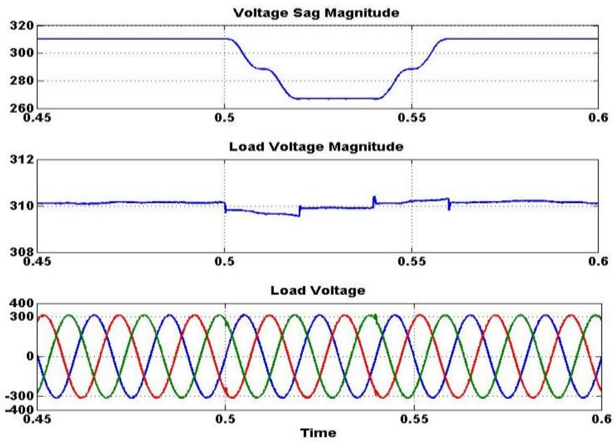

Figure. 5 (b) the magnitude of voltage sag and Load voltage at balanced voltage sag up to 0.76 pu (between 0.5 to 0.54 sec) for 0.0398sec

The simulated results of momentary voltage sag with field data based duration are shown in Figure. 5 (a) and (b). The time duration and sag depth of field are considered for comparison with simulation. The results include the amplitude and magnitude of voltage sag and load voltages for balanced voltage sag up to 0.76 pu for 0.0398 sec [3]. The actual field data for the same condition is shown in Figure. 6 (a) and (b). The same sag produced with same time duration and with different voltage level is shown for the purpose of visualization of the event in Figure. 6 (b). The simulated result of instantaneous voltage sag for 15% sag is shown in Figure. 7 (a) and (b) and its actual field data is shown in Figure. 8 (a) and (b).

The simulated result of instantaneous voltage swell for 10% swell is shown in Figure. 9 (a) and (b) and its actual field data is shown in Figure. 10 (a) and (b). Single Line to Ground fault based voltage sag events causes a voltage sag less than the lower limit of 55 V of Phase A during the entire study period. The nominal voltage is set for 62 V. The voltage sags for less than 0.9 pu has been observed for almost 5 % of the entire time period [3].

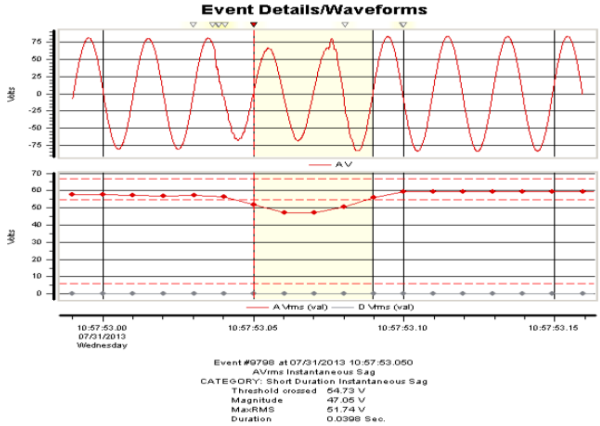

Figure. 6 (a) Field data for balanced voltage sag up to 0.76pu for 0.0398sec.

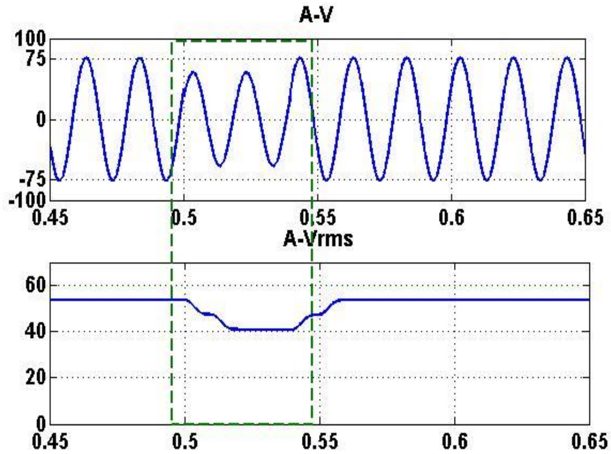

Figure. 6 (b) Simulated output for balanced voltage sag up to 0.76pu (between 0.5 to 0.54 sec) for 0.0398sec

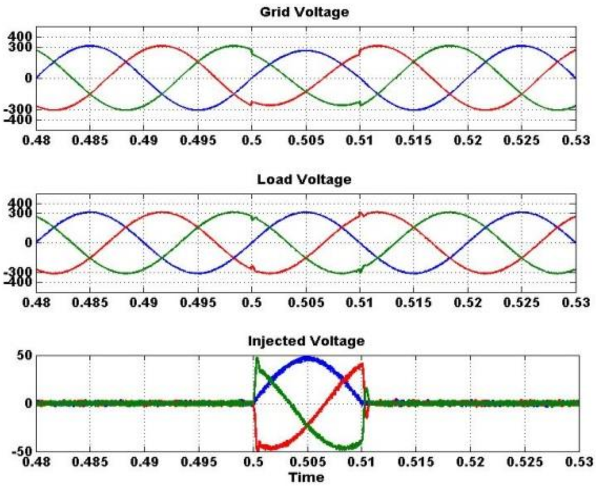

Figure. 7 (a) the amplitude of Grid voltage, Load voltage and the injected voltage for balanced voltage sag up to 15% dip (between 0.5 to 0.51 sec) for 10 ms

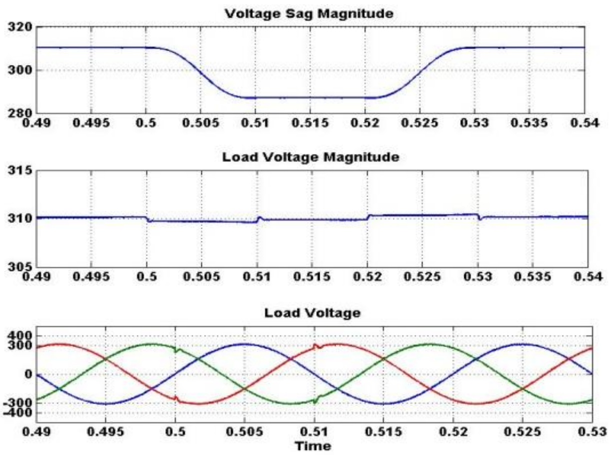

Figure. 7 (b) the magnitude of voltage sag and Load voltage at balanced voltage sag up to 15 % dip (between 0.5 to 0.51 sec) for 10 ms.

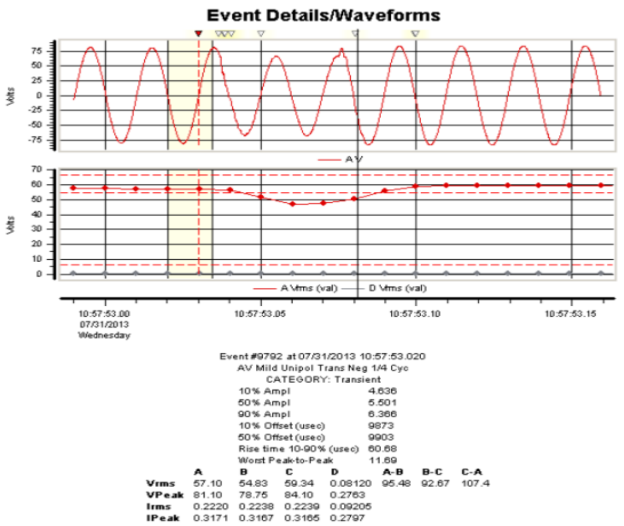

Figure. 8 (a) Field data for balanced voltage sag up to 0.85 pu for 10 ms

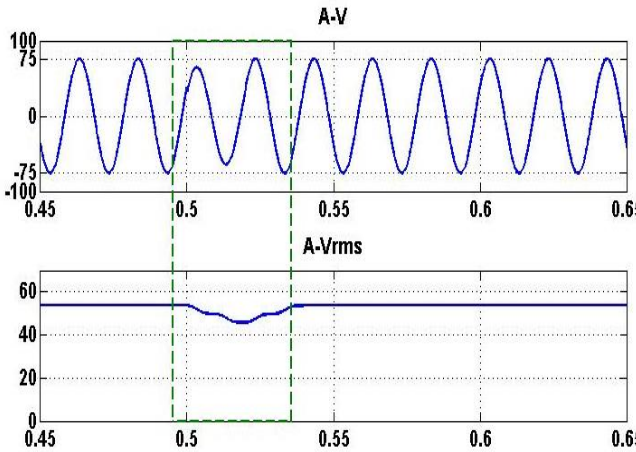

Figure. 8 (b) Simulated output for balanced voltage sag up to 0.85 pu (between 0.5 to 0.51 sec) for 10 ms

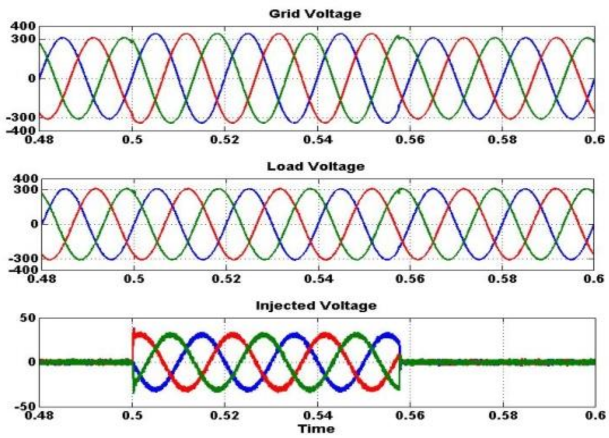

Figure. 9 (a) the amplitude of Grid voltage, Load voltage and the injected voltage for balanced voltage swell up to 1.1 pu (between 0.5 to 0.55 sec) for 0.05 sec

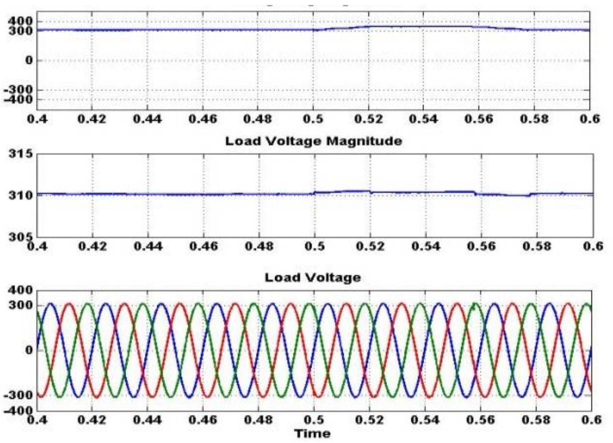

Figure. 9 (b) the magnitude of voltage swell and load voltage for balanced voltage swell of 1.1 pu (between 0.5 to 0.55 sec) for 0.05 sec

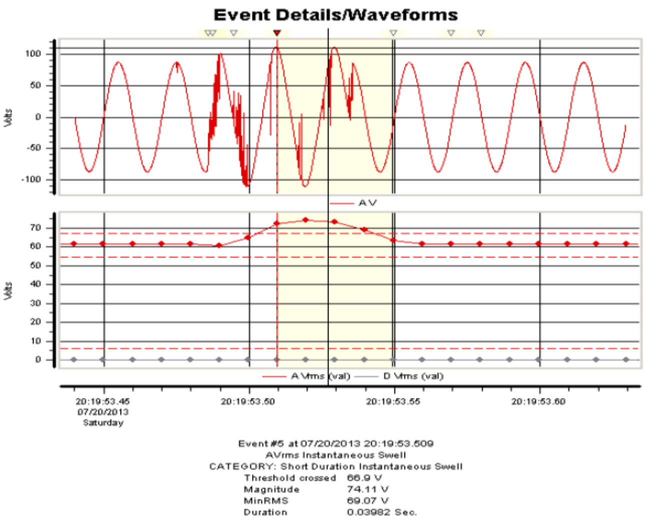

Figure. 10 (a) Field data for balanced voltage swell up to 1.1 pu for 0.05 sec

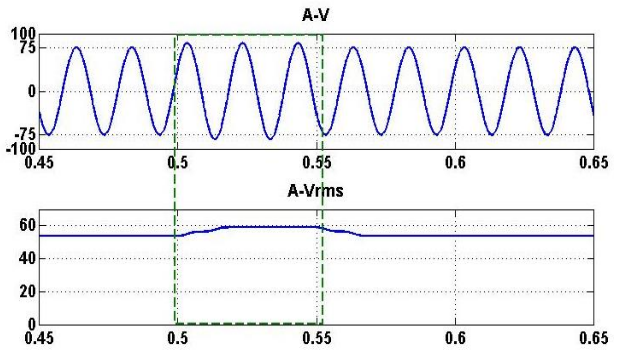

Figure. 10 (b) Simulated output for balanced voltage swell up to 1.1 pu (between 0.5 to 0.55 sec) for 0.05 sec

To demonstrate the ability of control strategy , an unbalanced voltage is also generated using programmable voltage source in the simulation as shown in Figure. 11. For the clarity, the DVR is started at 0.06 sec to compensate only the unbalance. From 0.1 sec to 0.18 sec, unbalanced sag of 0.3 pu in R- phase, 0.2 pu in Y- phase and 0.25 pu in B- phase is generated and it is clearly shown that the control strategy is taking care of the unbalanced fault condition. And the voltage restoration is also shown in the Figure. 11.

The comparative study of the field data with simulated results show a clear idea of voltage restoration during sag and swell conditions. According to the report [3], the power quality events in a variable speed generator are less compared to fixed speed generator. Therefore, DVR can be a good solution to address these power quality issues to achieve the FRT capability effectively.

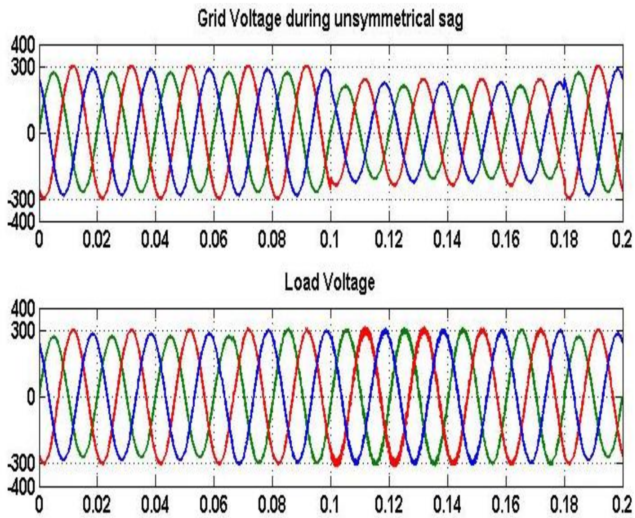

Figure. 11 The amplitude of Grid voltage, Load voltage and the injected voltage for a unbalanced voltage sag of 0.3 pu in R- phase, 0.2 pu in Y- phase and 0.25 pu in B- phase (between 0.1 to 0.18 sec)for 0.08 sec

5. Conclusion

Voltage sags and swells are very common power quality issues due to faults in systems connected to wind farms, which may lead to adverse effects like unintentional islanding. A Dynamic Voltage Restorer using feed forward based control with In-phase compensation principle has been used to mitigate the voltage sag and swells. This method has the benefit of improved series voltage injection utilization. The PWM firing signals to the inverter for injecting appropriate compensating voltage are generated using the feed forward compensation based control. The paper has dealt both symmetrical and unsymmetrical faults occurring in the wind farms during different sag and swell conditions. The sag depth up to 30% and swell up to 10% are mitigated efficiently by using this method. By comparing with the field data, we can suggest that DVR is a reliable option for voltage restoration at such fault conditions.

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