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POWER QUALITY ENHANCEMENT OF GRID CONNECTED WIND FARM USING DYNAMIC VOLTAGE RESTORER (ADAMA I WIND FARM IN ETHIOPIA)

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Abstract- Rising sensitivity of the loads with respect to power quality has grown-up the consideration of power system study and power quality enhancement systems. The fluctuation of voltage outside the normal working range due to faults may lead to unsuitable interruption of wind turbines. This thesis present $1.5MW$ grid connected Adama I Wind Farm in Ethiopia with the objectives to capture the optimal power from the wind and ensure voltage source for sensitive load. This paper deals with the effective voltage sag mitigation and Harmonic distortion effectively met IEEE 519-1992 standard under all Phase to ground fault compensation by using Dynamic Voltage Restorer (DVR), to regulate the terminal voltage of the wind farm and safe operation of sensitive load. The DVR utilizes a feed forward control-based algorithm to generate PWM. The simulation results are going to be carried out by MATLAB-Simulink to verify the operation and effectiveness of DVR during balanced voltage sag and swell conditions.

Keywords: Adama I Wind Farm, SRF, Feed forward control, Voltage Sag, DVR, MATLAB-Simulink

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1. Introduction

Ethiopia has superb wind power volume. According the [1], the capability is 18645MW, 4925MW, and 2005MW with wind velocity of 7.5~8m/s, 8~8.8m/s, and) greater than 8.8m/s respectively at a maximum height of 50 m. This shows that there is an encouraging situation to assemble massive scale wind farm. Adama one wind farm is located approximately ninety-five km from Addis Ababa and seven km from Adama, at elevations of 1741~2173 m. The topographical positioned of the wind power project is 39° 12' 10" E, 8° 34' 18" N. At the ground of the wind farm challenge is particularly included with shallow grass and small shrubs and a few gravels. It is a positive site for wind power project [2]. The size of Adama wind farm (phase-1) is $51MW$, with 34 units, and $1.5MW$ each unit. Thus, in the combination method of modelling, the number of parallel machines is set to 34 in Dig SILENT. Wind turbine is utilized permanent magnet generator, which is gearless and directly driven [3]. The converter system combined synchronous generator guarantees superior grid connection capabilities. But the converter-inverter system used in wind farms create harmonic distortion this may result a power quality problem within the wind farm and the grid connected to it. Among power quality problems harmonics and sags are more dominant. These sags and harmonic distortion are significant power quality problems in the power distribution system. One of the best keys to improve power quality at distribution is the dynamic voltage restorer (DVR). DVR is a kind of custom power devices that can inject active/reactive power to the power grids. This can preserve loads from instabilities such as sag and harmonic distortion. Often, DVR connected between sensitive loads feeder and source in distribution system. Its structures include lower cost, reduced size, and its fast dynamic response to the disturbance [4].

2. Methodology

In order to achieve the desired general objective of this thesis work the methodology is carried out as below.

- Modeling grid connected PMSG Based wind turbine system.
- Design Dynamic voltage restorer (DVR) for compensation of voltage.

2.1. Modeling grid connected PMSG Based wind turbine system.

Under this section, WTG data's of Adama I wind farm given in appendix 1. and appendix 2. are used to design PMSG based wind turbine system in order to feed reliable power for designed sensitive load [5]. Figure 1. express the simulation diagram that consists of single grid connected 1.5MW PMSG based (WT) disseminating power to 132kV grid through (7.3km,33kV) feeder and transformers (33kV/132kV) and (0.69kV/33kV) and Sensitive load is rated at 50 kVA at 95% power factor lagging and receives power from the grid at 132

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kV. There are two stepdown power transformers (132KV/15KV) and (15KV/380V) are utilized through total 10km transmission line in order to allow the utilization of low volage sensitive load.

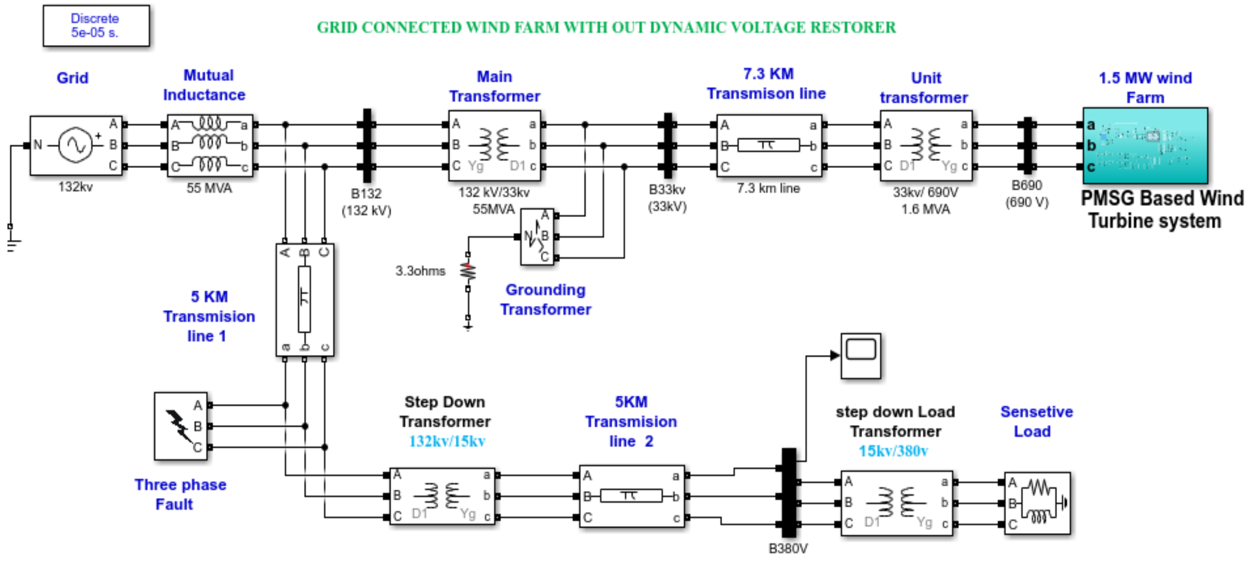

Figure 1. Electrical link model of grid connected sensitive load without DVR

2.2. Modeling Dynamic Voltage Restorer and its Controller System

The DVR should be designed to have negligible effect on the system, during faulted and non-faulted system states. The ratings of DVR components should be selected properly to ensure fast and reliable response. Figure 2. explain methodology to design the overall dvr system in order to protect sensitive Load from fault and safe operation of wind farm during faulty conditions [6]. which deserve consideration in the design of a DVR. Voltage source, PWM inverter, Injection transformer, Harmonic filter and Control system.

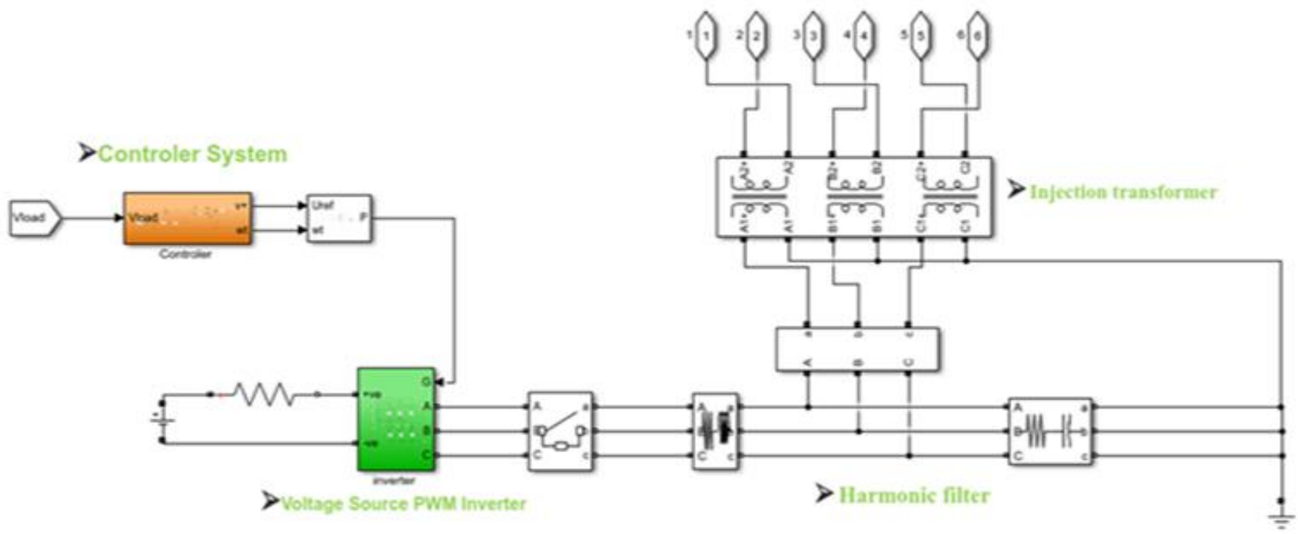

Figure 2. MATLAB/Simulink model of Dynamic voltage restorer (DVR)

2.2.1. Voltage source Inverter design

Voltage source inverter created on IGBT plans to generate the injection voltages to compensate for the voltage sag. Control of voltage wave form is restricted by the switching frequency of the inverter. MATLAB/Simulink model of the three-phase PWM inverter is shown in Figure 3. The three-phase full wave inverter bridge is built by six IGBT switches (S1, S2, S3, S4, S5, S6) and six anti-parallel diodes (D1, D2, D3, D4, D5, D6). The average output voltage (VR) is a function of the duty cycle (Dr) of the IGBT switch:

$$V_R = \frac{1}{1 - D_r} V_{Dc} \qquad [1]$$

$$Where \quad D_r = \frac{t_{on}}{T}$$

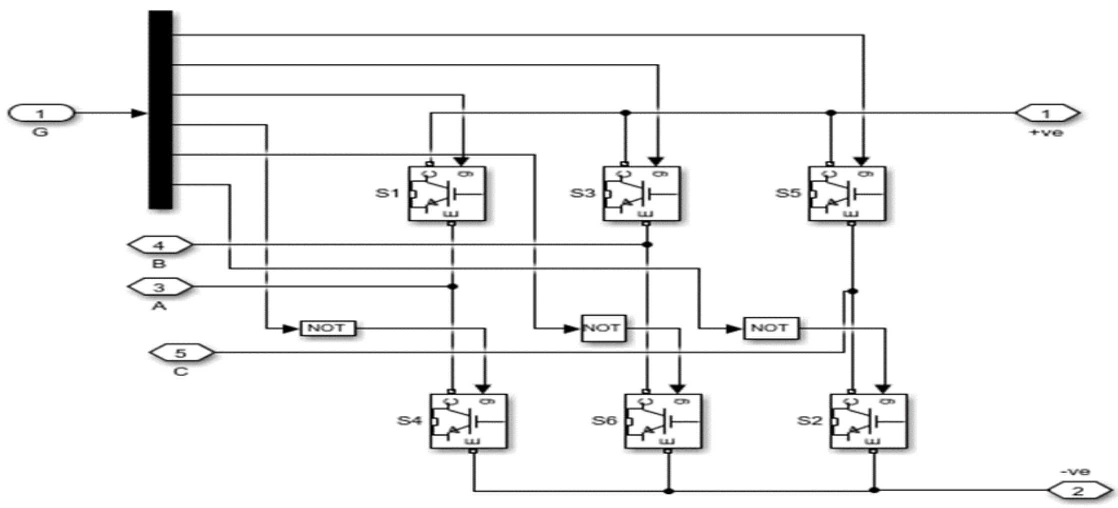

Figure 3. Simulink model of the three-phase PWM inverter

2.2.2 Injection Transformer Model

The injection transformers connect the DVR to the distribution network via the high voltage windings. In this modeling, twelve terminal three phase $6.6\,kVA$ and $3464V/140V$ (rms) ratings transformer is used. The secondary winding parameter of injection transformer are $Pn = 6.6KVA,\ fn = 50Hz$ and $Vn = 140Vrms$, the injection transformer that delivers compensated voltage for sensitive load have a transformer with capacity of $6.6\,MVA$, impedance percentage 10% and $3464V/140V$.

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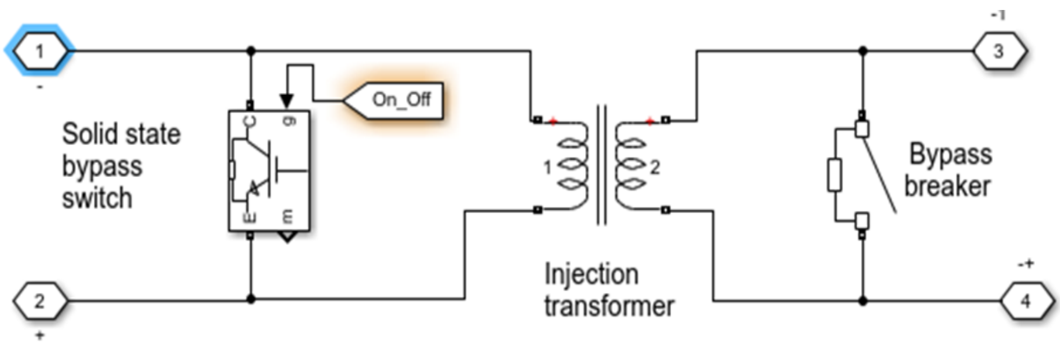

Figure 4. Single-phase circuit of injection transformer

The resistance, inductance and core parameters of windings are represented in the pu values. For each winding, the per-unit resistance and inductance are defined as: The base resistance and base inductance used for each winding are:

$$\begin{cases} R(pu) = \dfrac{R(\Omega)}{Rbase} \\ L(pu) = \dfrac{L(H)}{Lbase} \end{cases}, \quad \begin{cases} R(base) = \dfrac{(Vn)^2}{Pn} \\ L(base) = \dfrac{R(base)}{2\pi fn} \end{cases} \quad [2]$$

Where Pn, fn are transformer rated power (VA) and Nominal Frequency (Hz) respectively and Vn is nominal voltage (rms) of corresponding winding, so depending up on above equation the base resistance of secondary winding is calculated

$$R_{base} = \frac{(Vn)^2}{Pn} = \frac{140^2}{6.6 \times 10^3} = 2.96\ \Omega \quad \text{and}$$

$$L_{base} = \frac{R_{base}}{2\pi fn} == \frac{2.96}{2 \times 3.14 \times 50} = 9.45\text{mH}$$

And also, base resistance of primary winding is calculated as,

$$R_{base} = \frac{(Vn)^2}{Pn} = \frac{3464^2}{6.6 \times 10^3} = 1818\ \Omega \quad \text{and}$$

$$L_{base} = \frac{R_{base}}{2\pi fn} = \frac{1818}{2 \times 3.14 \times 50} = 5.79\ \text{H}$$

Then per unit (pu) value of primary winding is calculated as,

$$R_{pu} = \frac{R(\Omega)}{R_{base}} == \frac{0.28}{1818} = 0.00015\ pu \quad \text{and}$$

$$L_{pu} = \frac{L(H)}{L_{base}} = \frac{1.11mH}{5.79H} = 0.00019\ pu$$

In the same way (pu) value of secondary winding is calculated as follow

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$$R_{pu} = \frac{R(\Omega)}{R_{base}} == = \frac{0.056}{2.96} = 0.0189\ pu \ \text{ and}$$

$$L_{pu} = \frac{L(H)}{L_{base}} = \frac{0.067mH}{9.45H} = 0.007\ pu$$

2.2.3. Single Tuned Harmonic Filter Design

The below figure 5. represent Harmonics Filters is called Single tuned filters (STF) are probably most common type of filter which is used for harmonic mitigation. The ratings of the inductance (L) and capacitance (C) are related with the maximum injection limit of the DVR

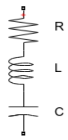

Figure 5. Construction diagram of single tuned filter

The harmonic filter can also provide a large percentage of reactive power for the power factor correction. When the capacitor, $Qcom$ KVA is installed in a system with a real power load P KW, the power factor can be improved from $Pf0$ to $Pf1$.

$$Q_{com} = p \times \left[\tan\left(\cos^{-1}(P_{f0})\right) - \tan\left(cos^{-1}(P_{f1})\right)\right] \qquad [3]$$

The capacity of a single tuned filter can be set to

$$Q_{com} = Q_f \qquad [4]$$

For multiple parallel single tuned filters, the capacitor corresponding to the h^{th} harmonic filter can be distributed approximately

$$Q_{fh} = Q_{com} \frac{I_h}{\sum_{n=1}^{h} I_h} \qquad [5]$$

were I_h denote the n[th] harmonic current and I_{fh} represent the capacity of the h^{th} harmonic filter. Also, the filter capacity Q_{fh} contains the capacity of capacitor Q_c and inductor Q_L, the relationship has the following.

$$\begin{cases} Q_{hC} = \frac{h^2}{h^2-1} Q_f \\ Q_L = Q_C - Q_f \\ Q_{hL} = \frac{1}{h^2} Q_C \end{cases} \qquad [6]$$

Capacitance of reactance at fundamental frequency, reactor size and capacitance are calculated as

$$\begin{cases} X_{hC} = \frac{kv^2}{Q_{hC}} \\ X_{hL} = \frac{X_{hC}}{h^2} \\ X_L = \frac{1}{2\pi fc} \end{cases} \qquad [7]$$

The other important term, which is tentatively to keep in mind during the designing of a filter, is quality factor. It determines the "sharpness" of the "tuning" of the passive filter and is given by the ratio of reactance at the resonant condition and resistance of the circuit as follows in equation

$$Q_f = \frac{X_c \; or \; X_L}{R} \qquad [9]$$

Where, Qf = quality factor

R= resistance of filter in ohms

In single tuned filter, the inductive and capacitive reactance at the tuned frequency should be equal. If $X0$ is the reactance the capacitance or filter reactor at its tuned frequency

$$X_0 = W_n L = \frac{1}{CW_n} = \sqrt{\frac{L}{C}} \qquad [10]$$

Harmonic pair, such as the fifth and seventh harmonics, have the potential for creating mechanical oscillation in turbine generator combination. So due to that one single tuned filter for 5^{th} is designed for the section for single tuned filter, typical value of quality factor fluctuates in between 50 to 150. The capacity of the transformer is 1000KVA with power factor 0.95 lagging. When the transformer is fully supplying power, the reactive power will be,

$$Q_{com} = S \times \sin(\cos^{-1}(Pf))$$

$$=1000\times \sin(cos^{-1}(0.95)) = 312.25KVAR$$

Using the equation (6), the capacity of capacitor Q_{5c} and inductor Q_{5L} for individual harmonics can be expressed as follows

$$Q_{5C} = \frac{h^2}{h^2-1} Q_f \text{ where h=1,2,3 and } Q_f = Q_{com}$$

Then for 5^{th} harmonic orders capacity of capacitor Q_{5c} and inductor Q_{5L} calculated as

$$Q_{5C} = \frac{5^2}{5^2-1} \times 312.25KVAR = 325.26KVAR$$

$$Q_{5L} = Q_{5C} - Q_{com} = 325.26KVAR - 312.25KVAR = 13.01KVAR$$

Then from equation (7) Reactance and Capacitance at fundamental frequency calculated as

$$X_{hC} = \frac{kv^2}{Q_{hC}} = X_{5C} = \frac{6600^2}{Q_{5C}} = \frac{6600^2}{325250} = 133.93\Omega$$

$$X_{hL} = \frac{X_{hC}}{h^2} = X_{5L} = \frac{X_{5C}}{5^2} = \frac{133.93}{25} = 5.36\Omega$$

Then the filter capacitance and inductance calculated as

$$C_5 = \frac{1}{2\pi f X_{5_C}} = \frac{1}{2\pi \times 50 \times 133.93} = 0.238\mu F$$

$$L_5 = \frac{X_{5_L}}{2\pi f} = \frac{5.36}{2\pi \times 50} = 17.06mH$$

The single tuned filter as shown on figure 5. encompasses an inductor in series with a capacitor. The inductor and capacitor are sized such that the branch impedance is zero near a harmonic frequency, which bypasses that harmonic. The capacitor delivers reactive power compensation. A resistor can be used in order to regulate the tuning's quickness. The quality factor is given by in equation (9).

$$Q_f = \frac{\sqrt{L/C}}{R} \quad , \quad \text{were}, 50 < Qf < 150 \; and$$

Then the value of resistance can be calculated as

$$R = \frac{\sqrt{L/C}}{Q_f} \qquad Let\ Q_f = 80$$

$$R_5 = \frac{\sqrt{L_5/C_5}}{Q_f} = \frac{\sqrt{17.06mH\ /0.238\mu F}}{80} = 3.15\Omega$$

2.2.4. Modeling Feed forward based DVR control System

As shown on figure 6. Source Voltage is sensed and is specified as an input to the abc/dq transformation block and source voltage is given as an input to the phase lock loop block, the block gives the information of sin, cos this is specified as an input to the abc/dq block, with these two inputs this transformation block gives Vd, Vq, and Vo information, this information is related with Vdact, Vqact and Voact which are the actual parameters. The quadrature and Vo axis is related with $zero$ (0) $p.u$ .The error formed is given as an input to the pi controller, the pi controller output is as soon as more given as an input to dq/abc block, and PLL information is also specified to dq/abc block. This block gives us the pulse information which is given as an input to PWM generator and from that gate pulses are generated; those gate pulses are for inverter reference signals Vdq is compared with the load voltages and the $Vinj$ is generated.

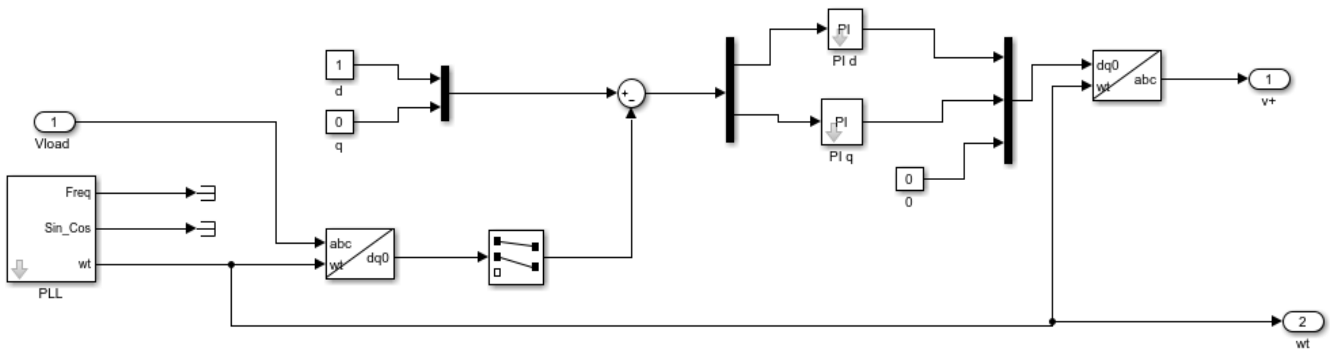

Figure 6. Model of Feed forward method of Dynamic voltage restorer controller

3. Simulation Result and Discussion

In this thesis, Simulation setups, results, discussions and related issues discussed. simulation model of the grid connected sensitive load with and without DVR was prepared and simulated in MATLAB library. The parameters of the considered system are specified in Table 1.

Table 1. Simulation parameters

Source voltage (Grid)	Line to line voltage	132 KV
	Supply frequency	50 Hz
	Line impedance	0.7 mH, 0.06 Ω
	Three phase short circuit level	25 MVA
	Step Down Transformer	$132kv/15kv$
Transmission Line	Line resistance (R)	0.2 (Ω/km)
	Line reactance (X)	0.4 (Ω/km)
	Length line 1 and 2	5km
Injection Transformer	Nominal Power	6.6 kVA
	Winding 1	3464 V (rms), R_1=1818Ω, L_1 =5.8mH
	Winding 2	140 V (rms), R_2=2.6Ω L_2=9.5 mH
Sensitive Load	Rating	50 kVA 0.95 lagging
	Nominal Phase to Phase Voltage	380 V (rms)
Load Transformers	Nominal Power	50KVA
	Primary Phase to Phase Voltage	15 kV (rms), R_1=2.16Ω, L_1 =8.6 mH
	Secondary Phase to Phase Voltage	380 V(rms), R_2=0.02Ω L_2 = 0.08 mH
Harmonic Filter	Filter inductance	17.06mH
	Filter capacitance	0.238μF

3.1. Phase to ground fault compensation

The proposed model should meet IEEE Standard 519-1992, the objective of the current limit and voltage limit of power system harmonic distortion. All Simulation results compered IEEE recommended standard limits.

To understand the performance of DVR along with control, a simple distribution network is implemented as shown at figure 7. There are three different of types of faults applied on the system.

- A. One-line to ground (LG) fault happens on system
- B. Two-line to ground (2LG) fault happens on system
- C. Three-line to ground (3LG) fault happens on system

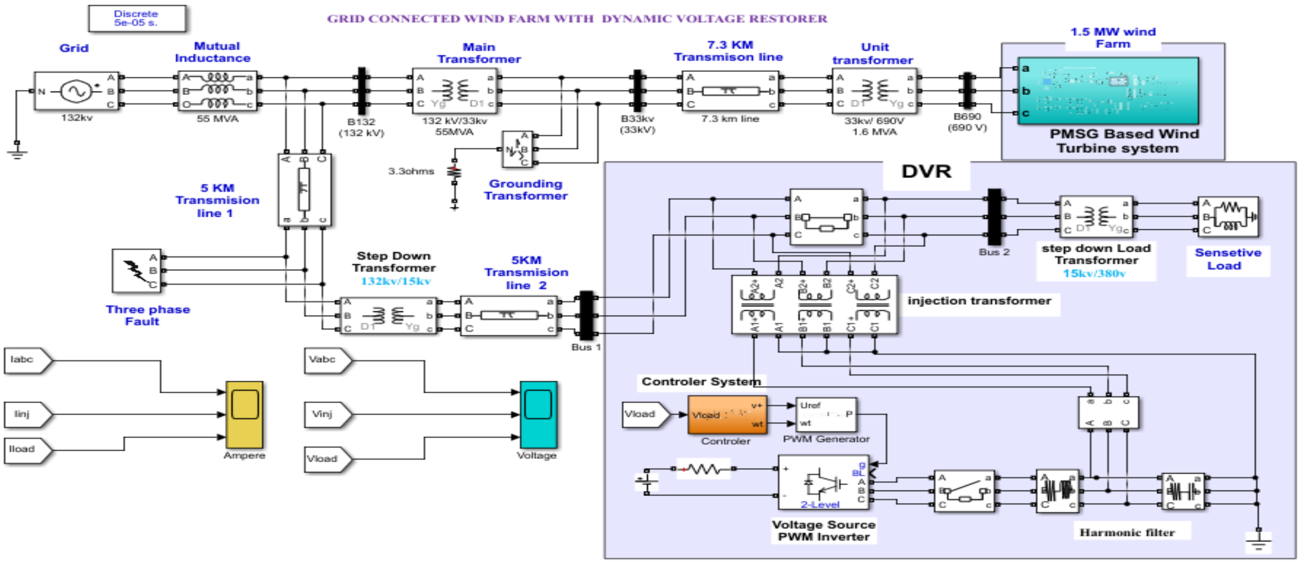

Figure 7. Electrical link model of grid connected sensitive load with DVR

Line to ground fault created voltage sag events causes a voltage sag less than the lower limit of Phases during the entire fault period. The magnitude of Grid voltage, grid current for balanced voltage sag dropped from its nominal values (between $0.3 - 0.6$ second) for 0.3 sec and the figure shows that the inaccurate or distorted wave form of source voltage and current at PCC when phase to ground fault is applied at time of $0.3 - 0.6$ second. The simulated results of momentary voltage sag with SLG fault are shown in Figure 8(a) and current wave form at (b). The consequences include magnitude of voltage sag stay for 0.3 seconds and distorted wave form has been observed.

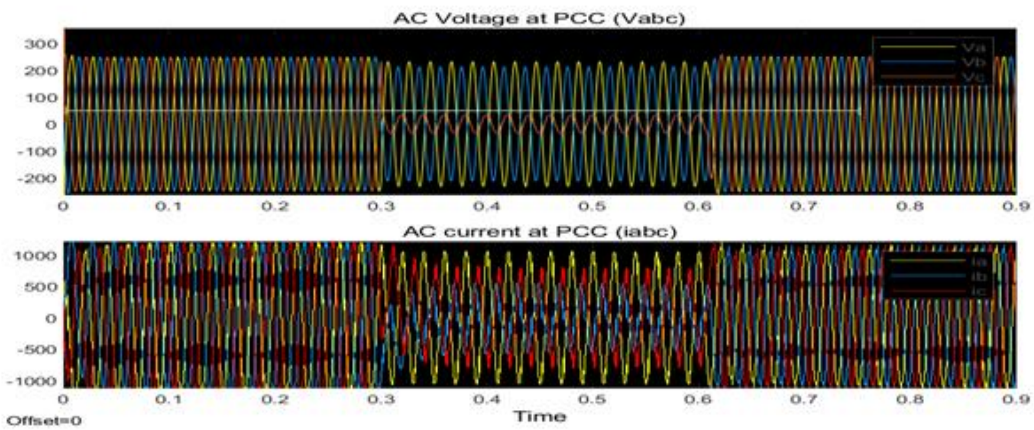

Figure 8. Source Voltage and Current wave form at PCC During SLGF

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Current harmonic spectrum and Source voltage at the PCC without DVR are given away at figure 9. The THD value corresponding to voltage is 23.41% whereas the current has $28.87\,\%$. The below harmonic stated spectrum fail to satisfy IEEE Standard 519-1992, the objective of this thesis is model proper sag mitigation which meet current and voltage harmonic distortion that recommended standard limit and no power quality issue on sensitive load.

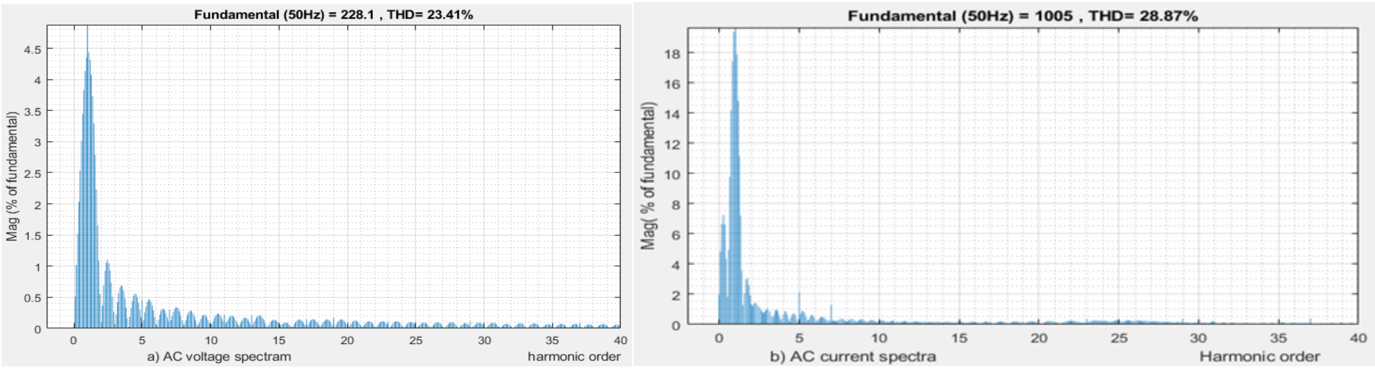

Figure 9. Harmonic spectrum of Voltage and Current at PCC, Without DVR

Figure 10. shows output voltage and current wave form during phase to ground fault compensation happen at $0.05 - 0.2s$ on a feeder. The simulation result of the DVR with controller for voltage sag circumstances with fault going on one phase in sensitive loads. Figure.10(a) represent wave form during SLGF is happen on a feeder, Figure 10(b) represent wave form during double line to ground fault is happen on a feeder and Figure 10(c) represent wave form during three phase to ground fault is happen on a feeder respectively. The primary waveform denotes the source voltage or grid voltage of the system, the next waveform figures out the injected voltage which is nothing but the compensation voltage. The third the voltage present across the sensitive loads.

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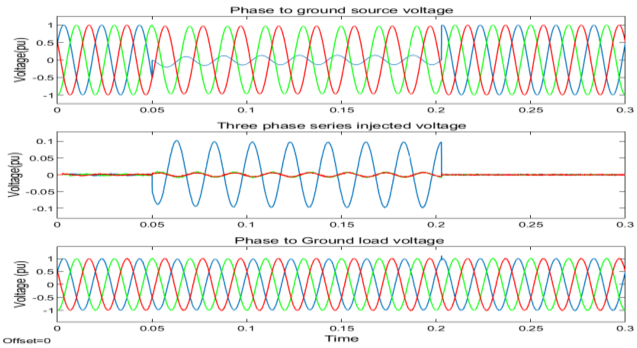
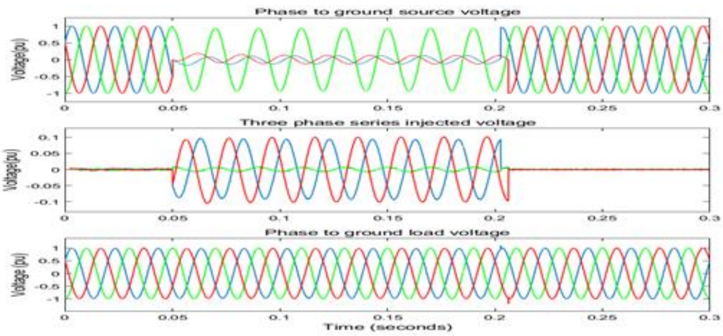
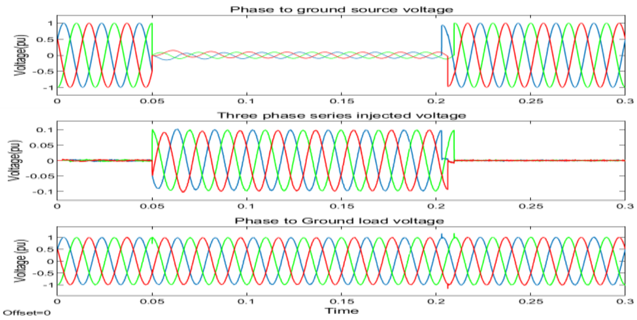


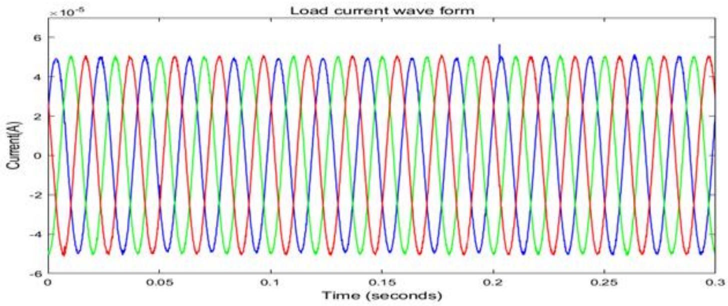
(a)



(b)



(c)



(d)

Figure 10. Output voltage and current of DVR during phase to ground fault compensation

At beginning there is no injected voltage and compensated voltage from DVR to the system because no voltage sag is detected. Once the sag starts at time 0.05 seconds, inverter produces the absent voltage so that the voltage sag does not affect the sensitive load. The main duty of DVR is providing the high-quality voltage to the critical loads. Figure 10(d) shows the load currents remain almost balanced and owing to high quality corrected load voltages

2.5. Harmonic Assessment during Phase to ground fault compensation

Based on IEEE-519 standards, $THDv$ at PCC is limited to five presents. To govern $THDi$, it needs to compute the ratio of short circuit current and full load current. The short circuit and the full load currents are computed as, for $50KVA$ transformer capacity with 8% of percentage impedance and $380V$ secondary winding voltage, the currents are calculated as follows:

$$I_{FL} = \frac{Transformer(KVA)}{\sqrt{3} \times Secondary\ voltage} = \frac{50KVA}{\sqrt{3} \times 380V} = 75.97A$$

$$I_{sh} = \frac{Full\ load\ current}{\% \times impedance} = \frac{75.97A}{0.08} = 949.6A$$

Then, ratio of the short circuit current to full load current turn into:

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$$\frac{I_{sh}}{I_{FL}} = \frac{949.6}{75.97} = 12.5$$

The distinct harmonic distortion assessment for current and voltage can be executed with a straight reflection of the simulated outcomes that is obtainable in the subsequent Table 2. and standard limit compliance assessment with the suggested in IEEE 519-1992 limits for distinct Total harmonic distortions (THD).

Table 2. Evaluation THD of Voltage and Current at PCC

h	THD_V % of voltage		THD_i % of current	
	Without DVR	With DVR	Without DVR	With DVR
3	8.2 %	0.39%	10.25%	3.51%
5	8.67%	0.23%	5.61%	1.36%
7	4.91%	0.09%	5.31%	0.5%
9	2.79%	0.08%	2.78%	0.54%

Now applying the IEEE 519-1992 recommended limits for individual current distortion and individual voltage distortion limit [7]. According IEEE 519-1992 lists the harmonic current limits based on the size of load with respect to the size of power system to which load is connected. ratio of the short circuit current to full load current equal to Isc/IL= 12.5 < 20 the recommending individual harmonic distortion is limited to 4.0 %. The recommending voltage limit for bus 132KV for individual voltage distortion is limited to 1.5%.

Now during DVR is off state all the 3rd,5th, 7th,9th voltage and current limit for harmonics distortion is failed to satisfy IEEE 519-1992 recommended limit with value of THD_V 8.2%, 8.67%,4.91%, 2.79% respectively and $THDi$ 10.25%, 5.61%, 5.31%, respectively. But as shown above Table 2 when DVR is on state both harmonic distortion limit for voltage and current within IEEE 519 Recommended standard limit, 0.39%, 0.23%, 0.09%,0.08% and 3.51%, 1.36%,0.5%,0.54% respectively. Therefore, the designed DVR is meet the objective of the paper.

4.Conclusion and Recommendations for Future Work

The aim of the thesis is to develop control strategy to improve the system response and injection capability of DVR for power quality improvement of grid connected wind farm. DVR is capable of compensating the various voltage disturbances like one-LG, 2-LG and 3LG faults at 300ms. It does not require energy storage system, which reduces the cost of using this device in distribution system and it has a quick dynamic reaction. In the normal conditioned DVR does not affect system performance but during abnormal condition DVR

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compensates the load voltage The proposed DVR has shown the ability to mitigate the voltage sags at the PCC. Additionally, the system has effectively met IEEE 519-1992 harmonic standard under all fault conditions. The area of aspect encompassed by means of this thesis and the answers and techniques explored on this thesis work may be additional preeminent to similarly studies areas, as in line with the subsequent areas The difficulty of FRT of PMSG throughout grid faults may be reconsidered the use of opportunity aggregate approaches, which includes (UPFC) and different reactive power source.

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6. Appendix

Appendix 1. Wind turbine Parameter Specification

Parameter	Value
WTG Version	GW 1.5/77
Wind turbine nominal power (MW)	1.5
Number of wind turbines	1
Wind turbine inertia constant $(H(s))$	4.32
Rotor diameter (m)	77
Rated wind speed	11m/s

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Appendix 2: Permanent Magnet synchronous generator parameter specification

Parameters	Value
Generator Type	PMSG, 1.5MW, 620V, 12.7 Hz, multi- pole (non-salient pole)
Rated Mechanical Power	1.5MW
Rated Apparent Power	1.6 MVA
Generator inertia	35000(J/kg.m2))
Rated Power Factor	0.97
Stator phase resistance $(Rs)\ ohm$	0.006Ω
q-axis phase inductance $(Lq)\ (H)$	0.395mH
d-axis phase inductance $(Ld)\ (H)$	0.395mH
Rated Rotor Flux Linkage (φ)	1.48wb
Viscous damping	1.5
Static friction (β)	0.01N m s
pole pair (p)	44
Speed Range	9-17.3 rpm
Rated current	680A