Mitigation Of Voltage Sag/Swell Using High Frequency Based Series Voltage Regulator For Distribution Transformer

Priyanka Wature, P.S. Swami

Abstract: Voltage sag/swell is frequent and unwanted power quality event observed in distribution system. Though it does not affect many loads but Service disruption and failure of electricity can be easily found in voltage sensitive equipment. To protect such equipment series voltage regulator for distribution system which can mitigate voltage sag/swell is proposed. The proposed system consists of power frequency transformer followed by power electronic module and load circuit. During abnormal condition compensating voltage (V_c) generated by power electronic module get added to supply voltage (V_{in}) to regulate voltage across load. The proposed system is effective to detect any disturbance in low voltage distribution system. Simulation results using MATLAB/SIMULINK are presented in this paper to verify productiveness of proposed system.

Index Terms: Converters, distribution transformer, power frequency (50HZ), power electronic module, voltage sag/swell, phase lock loop, phase shift.

1 INTRODUCTION

Due to progress of industrial automation systems and smart grids the power quality issue has become more important. so, in today's generation we need to give more emphasis on reliable power supply with good power quality. Commonly the end user consumers which are connected to low voltage distribution transformer are most susceptible to power quality issues. Among the many power quality issues the sag/swell phenomenon is most common phenomenon faced by many industrial consumer load on distribution side "[2], [4]". Any sudden dip in RMS value of voltage in the range of 0.1 pu to 0.9 pu for the duration of 0.5 cycles of AC wave to 1 min is termed as sag in voltage and the rise in RMS value of voltage in the range of 1.1 pu to 1.8 pu tor period of 0.5 cycles of AC wave to 1 min termed as voltage swell. voltage sag phenomenon is common in most of the power system and they are again classified according to the duration of their occurance i.e instantaneous, momentary, temporary. Nowadays, due to digitalization the sensitive devices such as computers may face maloperation including missing data, the relays and contractors in motor starters may fail to operate [5], so it is necessary to provide protection to such sensitive devices against voltage sag and swell. At present there are many solutions available to compensate voltage sag/swell on distribution feeder. The method includes placement of on load tap changer on distribution transformer which provides varying output voltage to the required level but voltage variation is not smooth it is stepwise and it has narrow range of output regulation and they are not firm sufficient to eliminate effect of voltage sag on consumer side "[6], [7]". The another option is uninterruptable power supply (UPS) is electrical device that provide power when main power supply fails but it should have same power rating as that of load.

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Furthermore there are many power electronic built power devices such dynamic voltage restorer (DVR), dynamic gas correctors provides solutions for voltage sags at minimum cost. Most common solutions for voltage sag on distribution transformer is dynamic voltage restorer (DVR) which is sandwiched in the middle of supply and critical load which inject dropped voltage in series with load [8], [9], [10]. DVR uses bulky energy storage devices i.e DC link capacitors and extra bulky power frequency transformer which causes major challenges in integrating them with existing system. In order to mitigate the disadvantages of all previous developed voltage sag mitigation techniques the new system is proposed which can be directly integrated with distribution transformer without any modification to the existing system is suggested in this paper. The proposed system requires medium frequency or high frequency transformer which reduces its weight and volume by 50% and 70% respectively [13]. It uses power electronic module which has power rating less than load rating. It does not need energy storage devices thus it reduces size of system. And also reliability is improved "[11], [12]". The proposed system consist of power electronic module connected between secondary side of power frequency transformer and critical load. The power electronic module uses converters and high frequency transformer to generate compensating voltage (V_C) which is get vectorly added to input voltage (V_{in}) to compensate voltage sag/swell. The major benefits of proposed system are.

1) It eliminate use of bulky energy storage devices i.e DC link electrolytic capacitor.
2) Power electronic module has to function only during sag/swell condition so it has to carry only partial power.
3) Due to limited power processing, power electronic module has lower power rating of converter.
4) For interconnection of this proposed system with existing distribution transformer there is no need of replacement or modification to the existing system.
5) Due to bypass switch, protection to power electronic module can be provided during external fault conditions.
6) fast system response is possible.

2. PROPOSED DISTRIBUTION TRANSFORMER CONCEPT AND TOPOLOGY

The proposed distribution transformer model includes two elements distribution transformer and a power electronic device based module (PE) as seen in Fig. 1. The power frequency transformer is our distribution side transformer which is dry type which transforms normal voltage to low voltage. The secondary side of distribution transformer is linked to an output terminals of the PE module such that load voltage ($\mathbf{V_O}$) is addition of input voltage ($\mathbf{V_{in}}$) and the compensating voltage ($\mathbf{V_c}$) generated by PE module during sag and swell. The power flow during swell condition is reversed. The efficiency of this system is mainly based on the amount of bypass power carried by PE module, during bypass mode the efficiency is maximum because power processed by PE module is zero.

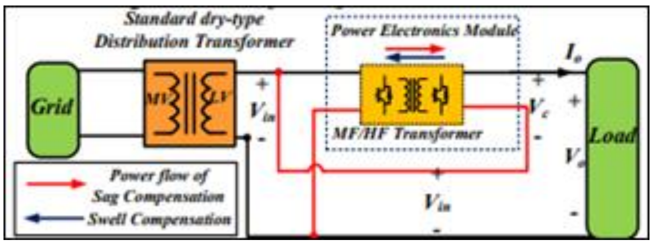

Fig.1.*Basic structure of proposed distribution transformer with PE module*

3. OPERATING PRINCIPLE OF POWER ELECTRONIC MODULE

The complete block diagram of power electronic module for distribution transformer is shown in Fig.2. The power electronic module composed of four single phase H bridge converters. Converter M1 which is acting as rectifier is connected to secondary of distribution transformer which operate at 50/60 HZ. There is high frequency(HF) transformer imposed between converter M2 and M3 to reduce the power rating of PE module. The power frequency converter M4 allows the connection with existing load system through LC filter, and controller detects and generates compensating voltage to compensate voltage sag/swell.

The PE module operates in two modes

1) Bypass mode

This mode is occur when system is in normal condition. In this mode the PE module does not process any power. due to this less losses occur. The grid-side voltage ($\mathrm{V_c}$) is straight joined to the output side by terminating a bypass switch Q2 and by opening a bypass switch Q1.

2) Voltage compensation mode

This mode occur during voltage sag/swell situation. In this mode the switch Q1 is closed and switch Q2 is open. The bypass switch is operated by voltage detection system and the mode compensating or bypass is decided by voltage magnitude varies in the grid. During voltage sag condition $\mathrm{V_o}$<$\mathrm{V_{in}}$ the compensating voltage generated by PE module ($\mathrm{V_{in}}$-$\mathrm{V_o}$) will get added to supply voltage, and during voltage swell condition $\mathrm{V_o}$>$\mathrm{V_{in}}$ the voltage($\mathrm{V_{in}}$-$\mathrm{V_o}$) 180° phase shifted will get added to supply voltage. The compensated power flow equation for PE module is given as

$$\mathrm{Pc}=[|\mathrm{Vo}|.\cos\theta - |\mathrm{Vin}|.\cos\theta].|\mathrm{Io}| = |\mathrm{Vc}|.\mathrm{Cos}\theta\,.|\mathrm{Io}| \quad (1)$$

As the compensated power Pc is fractional of rated power due to this PE module require reduced rating.

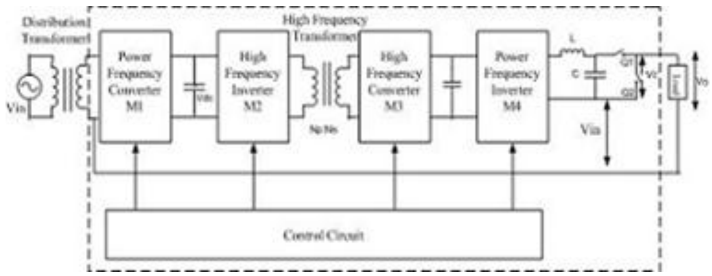

Fig.2. *Complete block diagram of power electronic module in proposed scheme*

4) PROPOSED METHOD

4.1 Main circuit

Fig. 3. Shows MATLAB/SIMULINK of proposed system. In which three phase programmable voltage source is connected to power frequency distribution transformer. Once voltage sag/swell occurs according to control circuit detection algorithm, the phase shift(φ) between the pulses of converter M2 and M3 decides the amount of compensating voltage to be injected in load circuit. The relationship between range of compensation and phase shift between MF/HF transformer having turns ratio is $\mathrm{N_p}$:$\mathrm{N_s}$ is

$$\mathrm{V_c} = \frac{\emptyset}{\pi}.\left|\frac{\mathrm{k}}{1+\mathrm{k}}\right| \quad (2)$$

Where k is amount of voltage sag/swell magnitude in pu (k>0 for swell, k<0 for sag). Fig.3 shows the MATLAB/SIMULINK model for N_p:N_s ratio 1:1. It is observed that most deep compensation is done when turns ratio of HF transformer is N_p:N_s is 1:1.

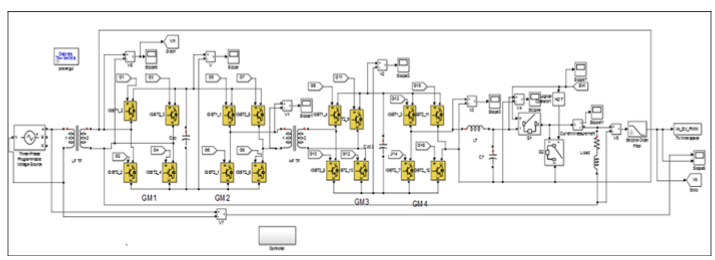

Fig.3. *Proposed system MATLAB/SIMULINK model*

TABLE 1 *SYSTEM DATA*

Parameters	**Value**
Power frequency T/F voltage ratio	230/80 V
Switching frequency of HF T/F	3000HZ
Rated VA of HF T/F	850 VA
Output filter inductance	4mH
Output filter capacitance	7.5µF
Small coupling capacitor C_{dc}	0.8µF
Load resistance	10Ω
Load inductance	1mH

HF T/F=High frequency transformer, VA=Volt Ampere
Table 1 shows main circuit parameters [3].

4.2 Control circuit algorithm

Fig. 4 shows the controller for series voltage regulator it consist of mainly three blocks voltage sag/swell detection block, compensating voltage generation block, and load voltage control block, The control scheme first has to detect voltage sag/swell, this can be done by voltage sag swell detection block, voltage magnitude V_m shown in control scheme for voltage detection is obtained by

$$V_m = \sqrt{(V_{inA})^2 + (V_{inB})^2} \quad (3)$$

Where V_{inA} is normalized input voltage and V_{inB} is 90° phase shifted normalized input voltage. The voltage detection signal (S_{ref}) is generated by subtracting (V_m) from normalized dc reference signal ($V_{o\ dc\ ref}$).

Condition for S_{ref} signal can be described as

When S_{ref} = 0 No sag or swell

> 0 Sag

< 0 Swell

This for S_{ref} signal is given to switch SW shown in Fig. 4 to operate switches Q1 and Q2. After detection of voltage sag or swell the required compensating voltage generated by voltage compensation block on the basis of amount of sag or swell, for this compensation block has to generate duty ratio D_{ff}. D_{ff} can be achieved by deducting normalized grid voltage signal ($V_{in\ normal}$) from normalized ac reference signal ($V_{o\ ac\ ref}$) i.e (V_{cref}) and dividing it by ($V_{in\ normal}$)

$$Dff = \frac{V_{o\ ac\ ref} - V_{in\ normal}}{Vin\ normal} = \frac{V_{cref}}{Vin\ normal} \quad (4)$$

$V_{o\ ac\ ref}$ is unity magnitude signal obtained by using phase lock loop circuit that constantly regulate signal to match with the frequency of supply signal "[14], [15]". The phase shift φ between the pulses of converter M2 and M3 decides compensating voltage V_c . The load voltage control block also has to generate duty ratio (D_{fb}).The phase shift φ can be obtained by adding (D_{ff}) and (D_{fb}) and then by converting duty ratio D into radian . The phase shift φ can be adjusted to generate V_c [3]. The gate signal for converter M4 given only if sag/swell is detected by sag/ swell detection block. For the generation of pulses for converter M4, the space vector pulse width modulation control method is used [16].

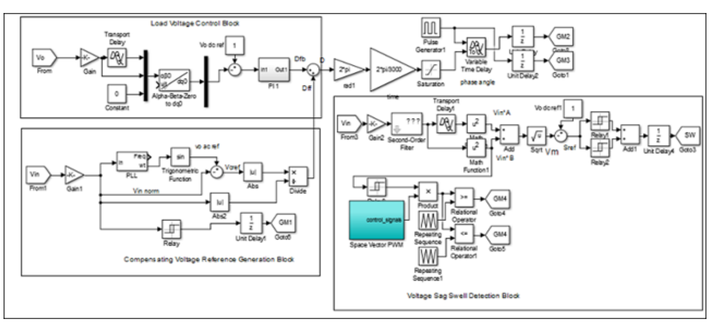

Fig. 4. MATLAB/SIMULINK of control circuit

4.3 Simulation results and discussion

Detailed simulation of series voltage regulator is implemented by using MATLAB/SIMULINK program in order to validate the operation. The various voltage sag/ swell conditions are given at any instant of AC cycle, through three phase programmable voltage source, and the results are shown below.

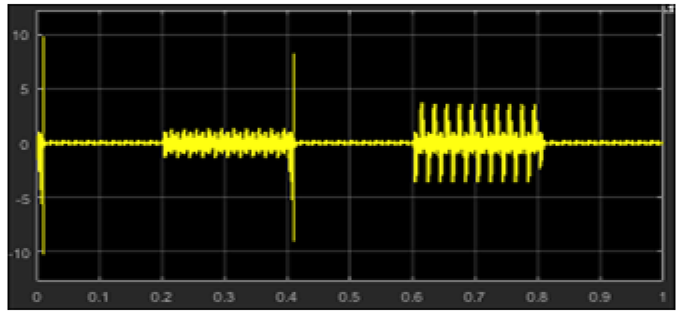

Fig. 5. *Compensating voltage V_c injected by series voltage regulator*

Fig. 5. shows compensating voltage injected by series voltage regulator in series with load circuit and it is zero during normal condition. Fig 6. Shows the voltage sag/swell detection signal given to bypass switches Q1 and Q2. Fig.7, Fig.8, Fig.9 shows the supply and load voltage for different voltage sag swell conditions. It is to be noted that during normal operation the power processed by power electronic module is zero. Due to filter and computation time required for control circuit small delay exist for detecting abnormal conditions.

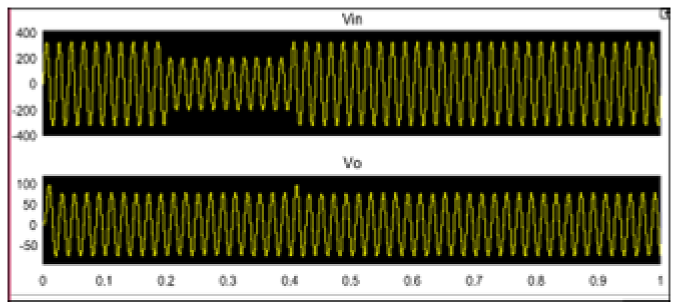

Fig. 7. *Source voltage V_{in} with 35% voltage sag and compensated load voltage V_o.*

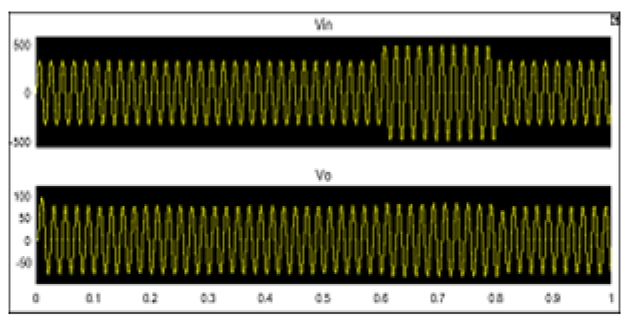

Fig. 8. *Source voltage V_{in} with 50% voltage swell and compensated load voltage V_o.*

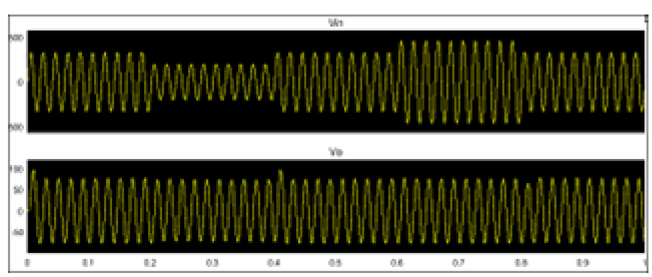

Fig. 9. *Source voltage V_{in} with 40% voltage sag and 40% swell and compensated load voltage V_o.*

5) Conclusions

This paper presents series voltage regulator to protect sensitive equipment against voltage sag/swell on distribution side using power electronic module (PE). The performance analysis is done using MATLAB/Simulink. During normal condition system working in bypass mode, feeding power from utility grid to direct load which allows PE module to have reduced rating to work only in transient period. The control circuit detects error signal and injects required compensating voltage using phase shift modulation technique. Simulation results shows that fast response and full compensation can be achieved. This proposed scheme can be easily integrated with existing distribution grid system for the improvement of power quality and for expansion of renewable energy sources in future.

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