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Research Article

Novel Design for Reduction of Transformer Size in Dynamic Voltage Restorer

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Abstract: The aim of the study is to design a Dynamic Voltage Restorer (DVR) with size minimized transformer. Transformer is the back bone and of vital importance in the power quality conditioners. However its cost is much higher than the other components of power system due to size of its core and windings. Overall cost can be reduced if we reduce these parameters. Transformer size is inversely proportional to the frequency of operation and flux density. Hence the reduction in the volume and the weight can be obtained by high frequency operation of the magnetic core. This study proposed a novel design of a power electronic circuit, which converts the low level frequency to high level at the primary of the transformer to minimize its size. At secondary side, a frequency is restored to 50 Hz and achieve the compensation. By using MATLAB SIMULINK based simulation results shows the proposed system decreases the transformer size with same power of transformer and capable to control the voltage sag and swell in efficient manner.

Keywords: Dynamic voltage restorer, flux density, high frequency transformer

INTRODUCTION

With the development of technology, the world is moving towards the concept of Smart Grid in which the size of the equipments gets reduced. The reduction of size give rises to the power quality issues. Smarter equipments have better performance and higher efficiency but they are also very sensitive to power quality as they require high quality of supply. Electrical power quality states that the waveforms of power distribution bus voltages and currents at rated magnitude and frequency should maintain a sinusoidal waveform (Acharya and Xu, 2007).

The Transformer placed at the substation is not the end-point of the power transmission but the beginning of power supply in distribution system. Therefore, it is very necessary to maintain the power quality of substation transformer. The rapid increase of non-linear loads such as electric and electronic equipments greatly hampers the power system quality at the transformer end by distorting the voltage wave-shape. The main issues associated with power quality are voltage sag and swell, phase shift, flickering, frequency deviation, transients, harmonics in current and voltage and zero sequence current (Zhang *et al*., 2013; JunKai *et al*., 2013; Kaczmarek and Nowicz, 2010; Lao *et al*., 2013).

The distortion in waveform shape is due to the harmonics produced due to extra losses in the transformers which increases the operational cost and heat produced in the power system resulting in the reduction of their expected lifetime (Kumsuwan and Sillapawicharn, 2013). The level of harmonics in voltage and current waveform is quantified by the measurement of Total Harmonic Distortion (THD) in which the harmonic content of a waveform is compared to its fundamental component (Sunil and Loganathan, 2012).

This present study is intended to design a power electronic circuit to decrease the size of the transformer with same power of transformer and to show the voltage restoration performance of the DVR with size minimized transformer with a test system. The simulation studies have been carried out using MATLAB/SIMULINK.

Dynamic voltage restorer: The Dynamic Voltage Restorer (DVR) is a welcome development as the device to compensate the voltage quality problems. DVR is a power electronic converter based device, designed to protect critical loads from the supply-side voltage disturbances (Madhusudan and Ramamohan Rao, 2012). And it is capable of generating or absorbing real and reactive power at its AC terminals (Fig. 1).

The basic principle of a DVR is simple: by inserting a voltage of desired magnitude and frequency, in order to restore the load-side voltage balanced and sinusoidal (Rao *et al*., 2013). When DVR is implemented in a low voltage level distribution network, transformer-less structure is usually better than the conventional transformer one by eliminating

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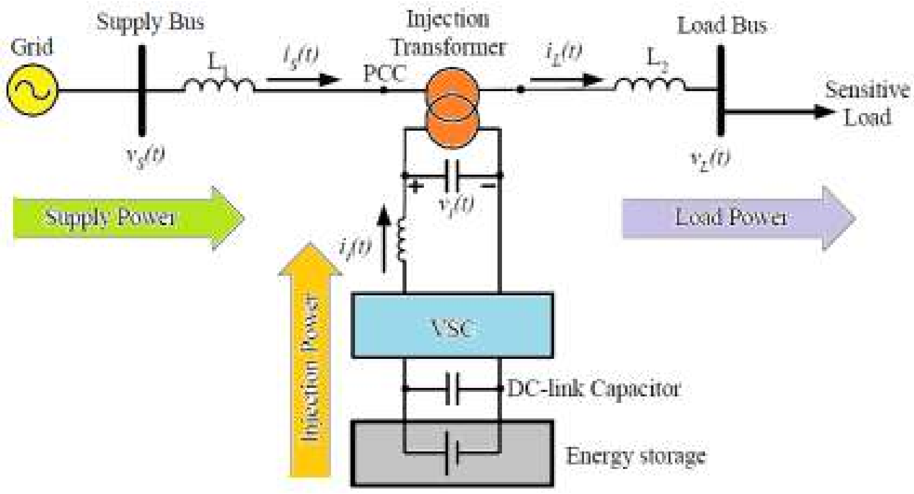

Fig. 1: General structure of DVR

the transformer phase shift, voltage drop, harmonics loss, bulky size, expensive cost and the problems of saturation and inrush currents associated with the transformer magnetization phenomenon (Sedaghati *et al*., 2013), but the inverter used in the DVR can have many different topologies, without proper filtering network load get affect severely by multiple harmonics.

In this study, minimization of transformer size in DVR, based on the power electronic converter is proposed. Firstly frequency vs. transformer size is analyzed and then the control strategy is described. Finally, simulation results using MATLAB/SIMULINK software will be presented to verify the ability of the proposed DVR in voltage restoration.

METHODOLOGY

Role of transformer in power quality conditioners: A transformer is an electrical device that transfers energy between two circuits through electromagnetic induction. A transformer may be used as a safe and efficient voltage converter to change the AC voltage at its input to a higher or lower voltage at its output. Other uses include current conversion, isolation with or without changing voltage and impedance conversion. Transformers are used to step up, step down or inject the volt to load or for isolation purpose. In power quality conditioners transformers are used for isolation and voltage injection purpose:

EMF per turn $$E_t = 4.44 f\phi_m \tag{1}$$

$$\phi_m = \frac{E_t}{4.44 f} \tag{2}$$

$$B_m = \frac{\phi_m}{A_i} \tag{3}$$

where,

B_m = The flux density
A_i = The net area of cross section of core:

$$A_i = \frac{\phi_m}{B_m}\ \text{mm}^2 \tag{4}$$

KVA (Power) rating of transformer:

$$Q = 2.22\, fB_m A_i k_w A_w \delta X 10^{-3} \tag{5}$$

Equation (5) shows if the frequency increases the power rating of transformer also increases.
Window area of transformer:

$$A_w = \frac{Q}{2.22\, fB_m A_i k_w \delta X 10^{-3}}\ \text{m}^2 \tag{6}$$

Based on the above Eq. (6) the supply frequency contribute the main core and window dimensions.

Current rating of primary side: The injection transformer is connected in series with the sensitive load which is to be protected by the DVR. Thus the current rating of the injection transformer is primarily determined by the rated capacity of the sensitive load. However, when sizing the current-carrying capability of the injection transformer, the effects of the high-order harmonics on the transformer should be included.

Turns-ratio selection and short circuit impedance consideration: The selection of the transformer secondary voltage and current ratings and its turns-ratio are interrelated. Starting with a given turns-ratio and as the transformer primary ratings are known, the secondary Voltage and Current ratings can be determined. The Current-carrying capability and the

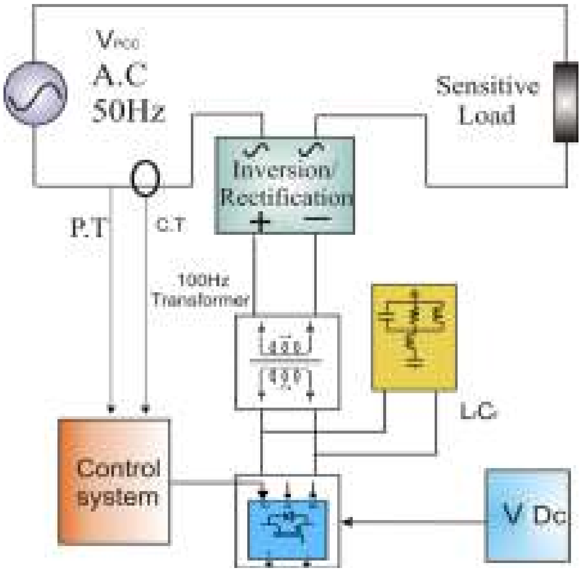

Fig. 2: Proposed DVR

blocking voltage of the switching devices can then be readily determined.

The short-circuit impedance will affect the fault current through the transformer. This impedance will also affect the design of the filtering system. However, as the power system is usually operating under normal conditions, the primary concern when considering the specification of the short-circuit impedance of the transformer is the voltage drop across it during the normal operations of the power system. When the inverter-side filtering scheme as shown in Fig. 2 is used, the effect of the filtering system on the voltage drop must be considered.

Proposed dynamic voltage restorer: The Figure 2 shows the Proposed Voltage Restorer. The important modification of conventional DVR to proposed DVR is the introduction of bi directional inversion and rectifications stage which allows the current bidirectional. Instead of 50 Hz injection transformer 100 Hz transformer is introduced in the proposed DVR so the size is reduced without affecting the power rating of transformer. Traditional control system is used to detect the voltage sag and swell's and fixed dc voltage is given to the DVR inverter which is used to inject the additional compensation voltage.

During the normal voltage time the inversion/ rectification mode block act as a rectification mode and the thyristors conduct at 0° firing angle. Due to this the output voltage of inversion/rectification module produces 100 Hz voltage. This voltage is fed to the proposed transformer and its normal operating frequency is 100 Hz. Without any fluctuation in the source side the control system produces the signal which makes no conduction of inverter so there is no injection voltage fed to 100 Hz transformer. So the output voltage is same as the input voltage.

During the voltage swell and voltage sag the inversion/rectification module act as inversion mode and control system produces 100 Hz injection voltage that is fed to input side of transformer.

During the voltage swell this injection voltage opposes the input voltage and compensated voltage is fed to the load and during the voltage sag this injection voltage associate/adds to the input voltage and compensated voltage fed to the load.

A passive filter is placed in front of inverter which is used to remove the switching harmonics. The impedance of the appliance is usually not low enough when compared to the filter inductor impedance for switching frequencies in practice. Therefore, an additional-C filter has to be placed across the DVR's terminals. An increase in switching frequency causes losses that are permanently presented during the operation of the DVR.

A very high filter inductance limits the dynamic characteristic of the DVR and increases the minimal stored energy in the capacitor (the creation of reactive power eliminates the inductor influence). The resistor causes additional losses, but during the normal

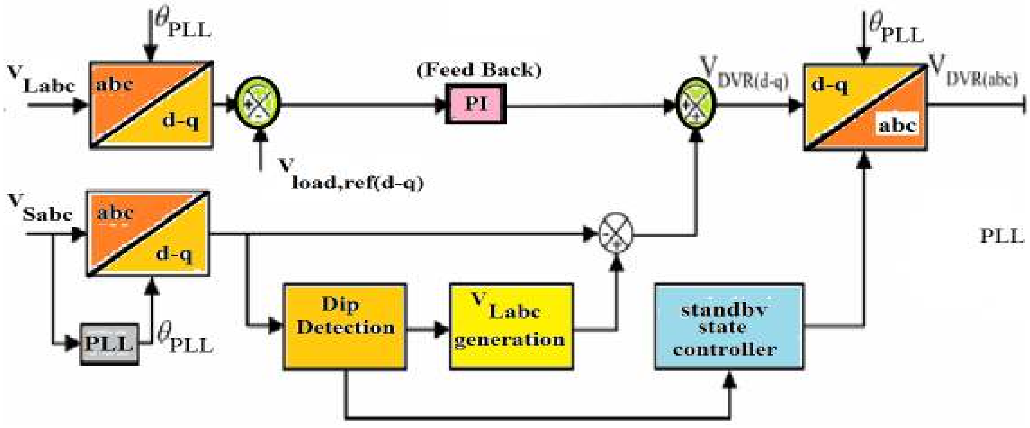

Fig. 3: Control system of proposed DVR

Fig. 4: Single line diagram of proposed DVR implementation

voltage in the grid almost zero voltage appears across the DVR's terminals. Therefore, the losses in the filter increase only during charging of the super capacitor and during voltage dips. The optimal choice among these contradictions is very difficult in practice. Theoretical background for filter design can be found (Wang *et al.*, 2006) (Fig. 3).

CONTROL SYSTEM DESIGN

The three-phase supply voltage is connected to a transformation block that converts to rotating frame (d q) with using Phase-Lock Loop (PLL). Three-phase voltage is transformed by using Park transform, from a-b-c to o-d-q frame:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = p \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{7}$$

$$p = \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{8}$$

$$\theta = \theta_0 - \int_0^t \omega t dt \tag{9}$$

The detection block detects the voltage sag/swell. If voltage sag/swell occurs, this block generates the reference load voltage. The sag detection strategy is based on Root Means Square (RMS) of the error vector. Closed loop load voltage feedback is added and is implemented in the frame in order to minimize any steady state error in the fundamental component. The injection voltage is also generated according to the difference between the reference load voltage and the supply voltage and is applied to the VSC to produce the preferred voltage.

Effects of various losses with respect to frequency:

$$\text{Hysteresis losses} = K_n f B_m^2 \tag{10}$$

Table 1: Case study parameters

Short circuit power	2.500 KVA
Equivalent inductance	157 μH
Equivalent resistance	0.007 pu
System frequency	50 Hz
Filter unit	
Filter inductance	369.500 μFH
Filter capacitance	55.980 μF
Sensitive load	
Supply voltage	200 V
Capacity	2 kVA

$$\text{Let } K = f B_m \tag{11}$$

$$\therefore K_h K_{Bm} = K_h K \frac{K}{f} \tag{12}$$

$$= K_h K \frac{K^2}{f} \tag{13}$$

Hence the hysteresis loss will decrease with increase in frequency.

∴ The total iron loss decreases when the frequency is increased. Eddy current losses remain constant even though the frequency is changed (Fig. 4).

Test system: Based on the above table values it concludes that in the 100 Hz transformer the size gets reduced more when compared to 50 Hz transformer.

RESULTS AND DISCUSSION

Simulation results for voltage sags: In this section representative simulation results are included to illustrate the performance of the test system described in this study. The simulation studies have been carried out using MATLAB/SIMULINK.

Figure 5 illustrates the voltage restoration performance of the DVR with size minimized transformer. The configuration of the studied system is as shown in Table 1 and 2. Voltage sag occurs at 0.1 to 0.5 msec shown in Fig. 5a. Observe that the proposed DVR quickly injects the necessary voltage components to maintain the load voltage. The DVR injected voltage and the load voltage are shown in Fig. 5b to d, respectively.

Table 2: 50 and 100 Hz transformer injection transformer

50 Hz transformer	100 Hz transformer
$\phi_m = 6.576$ wb	$\phi_m = 4.65$ wb
Net core area $A_i = 5.978\times10^{-3}$ m^2	Net core area $A_i = 4.23\times10^{-3}$ m^2
Gross-core area $A_{gi} = 6.642\times10^{-3}$ m^2	Gross-core area $A_{gi} = 4.697\times10^{-3}$ m^2
Width of core = 0.0576 m	Width of core = 0.0485 m
Depth of core = 0.149 m	Depth of core = 0.126 m
AT = 1370 Amp/turn	AT = 969 Amp/turn
Window area = 4151.59 m^2	Window area = 2933.59 m^2
Width of window = 40.75 m	Width of window = 34.26 m
Height of window = 101.875 m	Height of window = 86.65 m
Primary turns 7536	Primary turns 5330
Secondary turns 137	Secondary turns 137

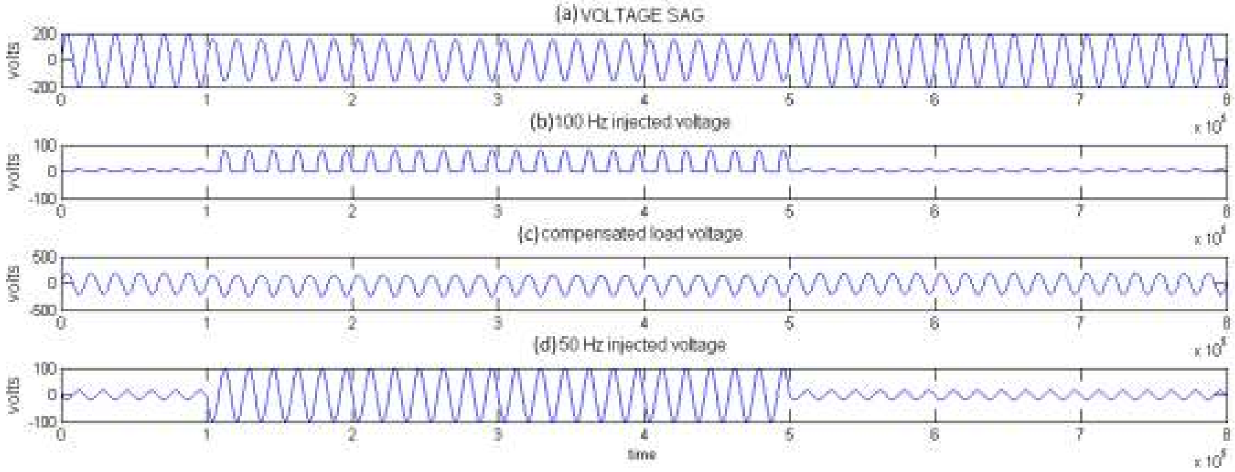

Fig. 5: (a) to (d) performance of DVR with size reduced transformer under voltage sag condition

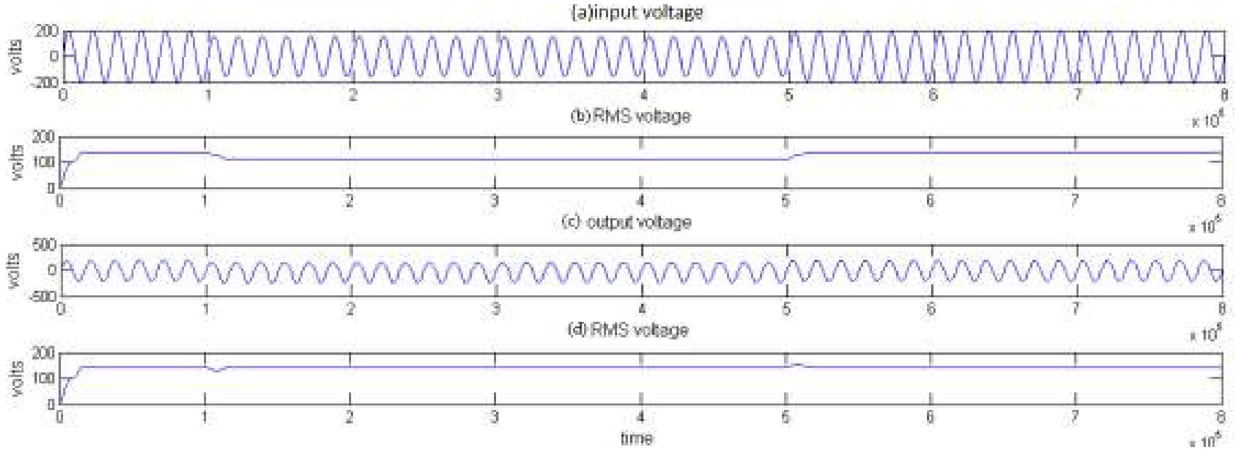

Fig. 6: (a) to (d) performance of DVR with size reduced transformer under compensating condition with RMS voltage

Figure 6 presents the results of simulation with RMS voltage indications. It is observed that the Fig. 6a voltage sag occur 0.1 to 0.5 msec and it shows Fig. 6b clearly shows the RMS value decreases. It can observed that during the fault the voltage at the PCC drops down to 20% of its nominal value. Figure 6c shows the compensated voltage and its corresponding RMS voltage is shown in Fig. 6d.

In Fig. 7a shows the voltage sag occurrence. The voltage sag starts at 1 msec and it is kept until 5 msec. Figure 7b shows the corresponding Total Harmonic Distortion (THD), it can be observed during the transition of compensating time the switching harmonics present and its level is 8% and at 5 msec also some harmonics present. Figure 7c and d show the sum of supply voltage and DVR injected voltage

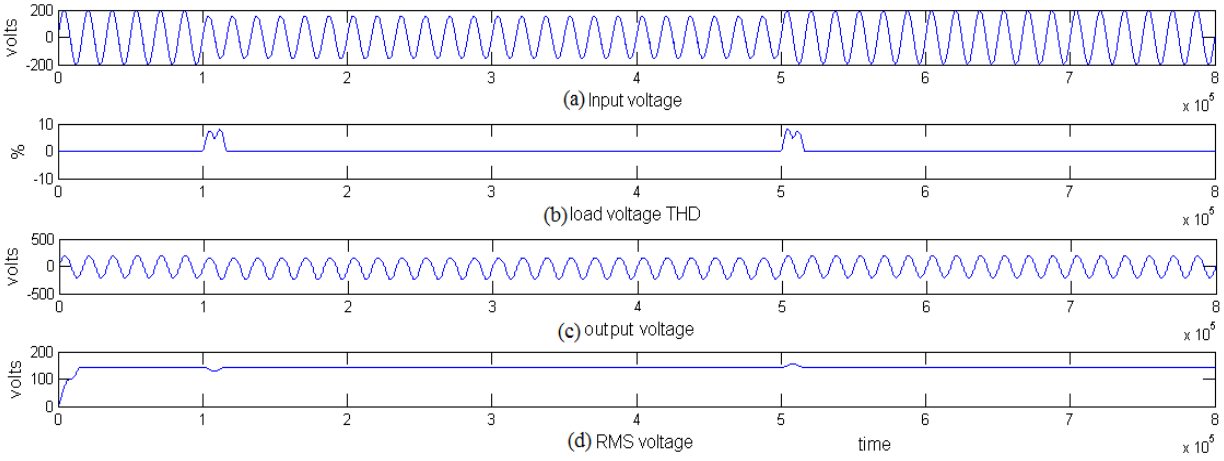

Fig. 7: (a) to (d) performance of DVR with size reduced transformer under compensating condition with THD

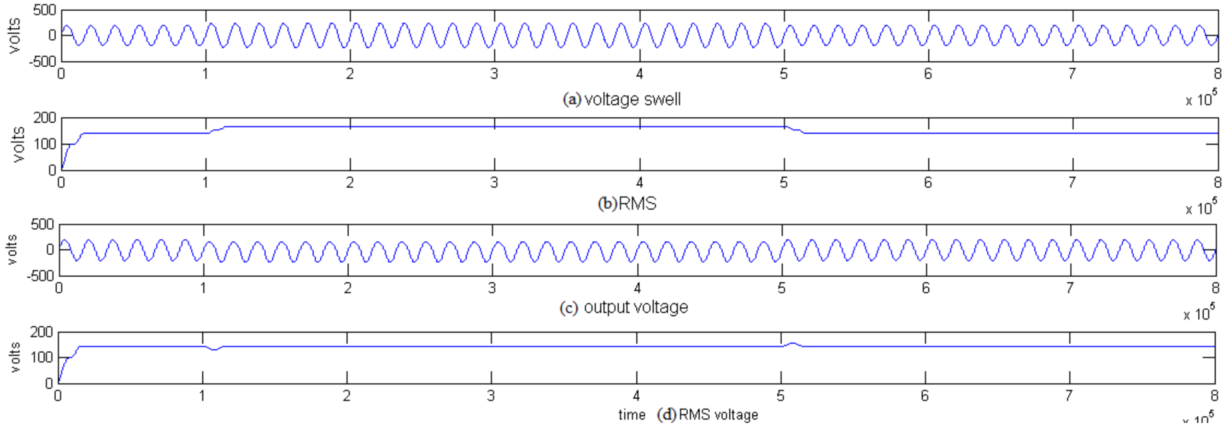

Fig. 8: (a) to (d) performance of DVR with size reduced transformer under voltage swell condition with RMS voltage

(compensated load voltage), respectively. As a result of DVR, the load voltage is kept almost constant at 1 pu throughout simulation.

Simulation results with voltage swell compensation: The performance of DVR for a voltage swell condition was investigated. It can be seen from the results, the load voltage was kept at the nominal. Figure 8 present the results of simulation for the test system when voltage swells occur, suddenly at 1 msec and close at 5 msec as shown in Fig. 8a. Figure 8b shows the corresponding RMS voltage (Fig. 8c). The Proposed DVR with size Reduced transformer regulate the voltage effectively as shown in Fig. 8d.

CONCLUSION

In this study, a novel DVR with reduced size transformer was proposed. As a result the Proposed DVR is a feasible device to compensate voltage sags and swells in power systems. Operating principles and the power circuit of the Proposed DVR was explained. Based on the simulations carried out, it is clear that a DVR can tackle voltage sags and swells when protecting sensitive loads. The novel DVR uses power electronic controlled transformers. So the size is reduced due to high frequency (100 Hz) operation and to inject high frequency voltage in to primary side and restore 50 Hz to the secondary side of transformer. Due to minimization of size of transformer this novel DVR is the cheapest solutions. Finally, simulation results and test data's proved that the novel DVR abilities in compensating voltage sags and swells with minimized transformer size.

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