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Switching Pattern for Transformer Cascaded Inverter in Dynamic Voltage Restorer Structure

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Abstract
Sensitive loads cannot tolerate voltage sags and swells in power distribution networks and lots of problems are engendered for them. Therefore, different instruments are planned to compensate voltage swells and sags. Between them dynamic voltage restorer (DVR) has found special importance, because it operates better than others for this purpose and restores voltage to its initial value conveniently. A DVR is a power-electronic controller that can protect sensitive loads from disturbances in the supply system. The DVR is installed in series to the network. In this paper 9 level cascaded inverters with cascaded transformers are used in DVR internal circuit, but the difference in magnetic flux in cascading transformers has adverse effects on the plan. Therefore, a new switching pattern is used.

Keywords: Cascade Inverter, Switching, Dynamic Voltage Restorer.

1. INTRODUCTION

Flexible ac transmission system devices or their sub-derivative custom power devices are efficient and often used in electrical power system [1,2,3,4]. They are based on solid state power electronic components [5,6,7]. Flexible ac transmission systems (FACTS) devices such as static synchronous compensator (STATCOM) [8,9], interline power flow controller (IPFC) [10,11], static synchronous series compensator (SSSC) and unified power flow controller (UPFC) [12] are those controlled by the utility, whereas

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the custom power devices such as active filter [13] and uninterruptible power supply (UPS) [14] are operated, maintained and controlled by the customer itself and installed at the customer premises.

Sub-derivative custom power devices based on PWM switching solid state compensators are used for improving power quality in the distribution system [15,16]. They are mainly of three categories such as series connected compensator like DVR [17,18], shunt connected DSTATCOM [19,20] and unified power quality conditioner (UPQC) [21] which is connected in both shunt and series on ac power supply. The DVR is a power-electronic controller. It has become popular as a cost-effective solution for the protection of sensitive loads from voltage sags and swells. DVR systems are bidirectional, so they can either generate or absorb active and reactive power. Therefore, DVR systems are known to provide a fast response to system disturbances and consume zero real power during steady state [22]. Voltage drop is one of the problems that is very important in distribution networks. It is caused by different factors for example one-, two-, three-phase short circuit and overload. Between them, three-phase short circuit and overload are more likely than others. These voltage drops are balanced or unbalanced that damage the sensitive loads seriously. Therefore, these must be compensated. DVR basic performance to solve this problem can be summarized as follows: DVR calculates this voltage drop and does this on the grid by the inverter; injected energy can be active or reactive. DVR connects to line in series most of the times but in some papers, it’s been put in the network in shunts. DVR consists of four fundamental parts: control circuit, inverter, filter and injection transformer. DVR energy secures by two following methods [23,24]:

(1) without energy storage: Conventionally these DVRs include converter, as a supply source. It is usually diode rectifier. In these topologies, saving is obtained on the energy storage system.

(2) with energy storage: Energy obtained from battery or one capacitor (save the energy from lying under normal circumstances). This method is used in this paper that is shown in Fig. 1. The capacitor supplies reactive power and the inductor consumes it [25]. As informed, one of the DVR parts is inverter. Inverters are divided into two-level and multi-level [26,27]. Multilevel inverters are paid attention for prevention of complex control methods that plan for two level inverters control, harmonic constraints due to SVPWM [28].

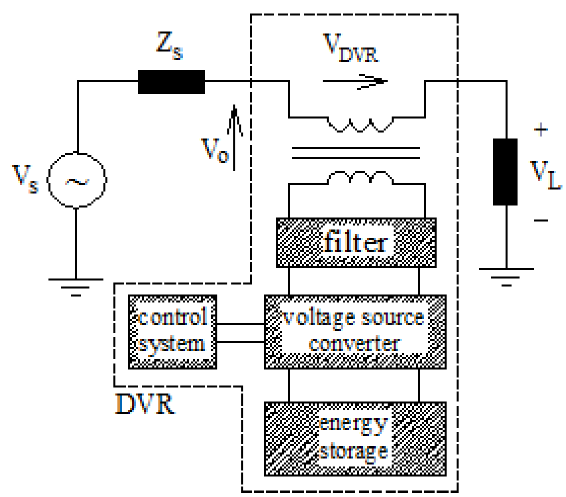


Fig. 1. Schematic diagram of a DVR [29].

Cascade inverters have many benefits than other inverters. Therefore, in this paper they are used in DVR structure. Until now in a few papers these inverters are used [30]. In their structure several H Bridge are used [31]. Basic defect of these inverters is their need to several dc sources. So, they are outfitted by transformer cascaded inverters. In recent years, multilevel inverter and its modified control schemes using cascaded transformers have been presented to obtain high quality output voltage with minimized number of switching devices. These multilevel inverter schemes efficiently increase the number of output voltage levels based on the different turn-ratio of the cascaded transformers [32]. But the difference in magnetic flux in cascade transformers has adverse effects on the plan. Thereupon the new switching strategy is used in this paper.

In this paper 9 level cascaded inverters with cascaded transformers are used in DVR internal circuit. This paper is organized as follows. The different control methods of DVR are presented in section 2. Fault detection and multilevel inverters are illustrated in section 3. In section 4, simulation results and discussions are given. Finally, conclusion is stated in section 5.

2. CONTROL STRATEGIES OF DVR

The DVR injects a set of three phase ac voltages in series and in synchronism with the supply voltage. These voltages have controllable amplitude, phase angle and frequency, which enable the DVR to restore the quality of the voltage at the load side when the quality of the supply voltage is distorted. So, to achieve this aim, on the basis of amount of loads sensitivity and DVR consumption, different control strategies are introduced as follows [33]:

2.1. The Presag Compensation

The pre-sag compensation method tracks voltage supply continuously and compensates load voltage during a fault to restore the pre-fault condition. For nonlinear loads that both voltage and phase angle must be compensated, this method is recommended. The DVR supplies the voltage that is the difference between the pre-sag and sag voltage [34].
When a fault occurs in other lines, left side voltage of DVR, V_S drops and DVR injects a series voltage, V_{dvr} through the injection transformer as following:

$$V_{dvr} = V_L - V_S \tag{1}$$

2.2. In-Phase Compensation

During in-phase compensation shown in Fig. 2, the injected DVR voltage is in phase with the measured supply voltage regardless of the load current and the pre-fault voltage.

The advantage of this method is that the magnitude of injected DVR voltage is minimized for constant load voltage magnitude, therefore, the apparent power of DVR is minimized. In this paper in Phase Control strategy is used. If the value of the load voltage VL is 1 pu, so V_{dvr} introduces as:

$$V_{dvr} = 1 - V_S \tag{2}$$

where I_L and ϕ are load current and load power angle. And the injected real power from energy storage to load is:

$$P_{dvr} = 3(V_L - V_S)I_L \cos\varphi \tag{3}$$

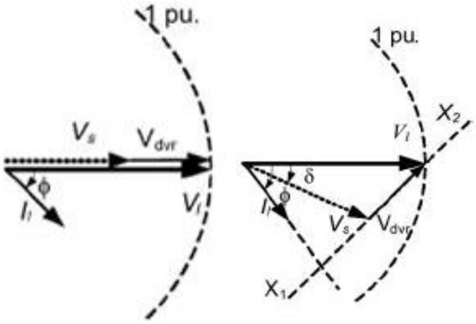


Fig. 2. (a) Phase control, (b) Minimal energy control [35].

2.3. Minimal Energy Compensation

If V_{dvr} deviates upwards, so that magnitude of load voltage is 1pu, injected real power will decrease. When V_{dvr} is kept in quadrant with I_L, real power injection is not required to restore the voltage by the DVR. Fig. 2 shows the phasor diagram of this technique. δ is the angle of V_L and α, is the angle of V_{dvr}. α can be obtained as:

$$\alpha = \pi / 2 - \varphi - \delta \qquad (4)$$

$$\delta = \varphi - \cos^{-1}\left[\frac{V_L \cos\varphi}{V_S}\right] \qquad (5)$$

3. DVR CONTROL

3.1. Fault Detection

When voltage is in steady state, it is better for loss reduction to inactivate DVR. Because in these conditions, in addition, it does nothing but reducing the voltage slightly. Therefore, fault detector system is used in DVR structure. It activates the DVR in fault occurrence. The circuit consists of a circuit breaker that controls the short circuit in the DVR. The breaker is normally closed.

When a fault occurs, control circuit opens the breaker. Its relationships are expressed in (6) and (7).

$$\left|V_{er,dq}\right| > V_T \qquad (6)$$

$$\left|V_{er,dq}\right| > \sqrt{(V_{ref,d} - V_{s,d})^2 + (V_{ref,q} - V_{s,q})^2} \qquad (7)$$

where, V_{ref} is reference voltage, V_S is left voltage of DVR and V_T is threshold voltage.

3.2. Control Method

In this paper in phase control strategy is used. After fault occurrence, V_S is transformed from ABC reference to dqo reference. It is obtained from Phase locked loop (PLL). PLL is used for reference voltage production. Because source voltage phase (before fault occurrence) is preferred, first it is saved with

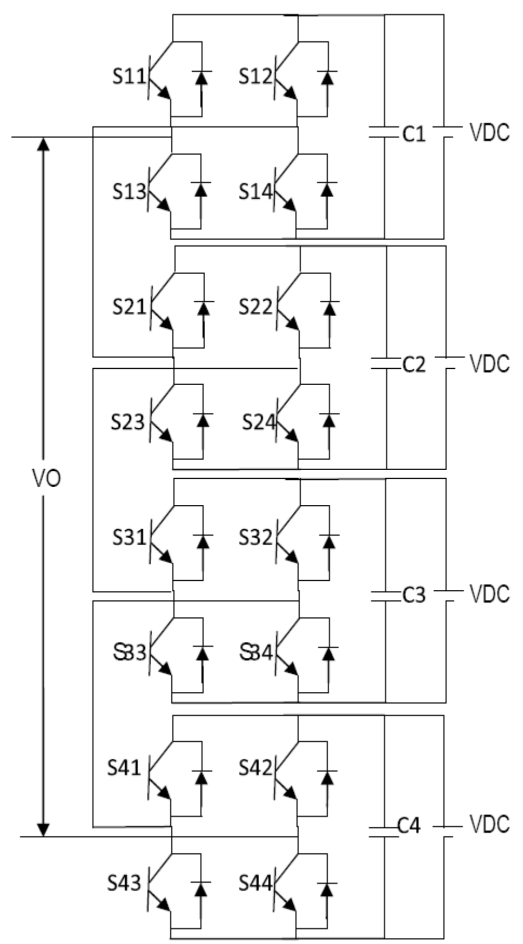


Fig. 3. CHML inverter with four H-bridge cells [32].

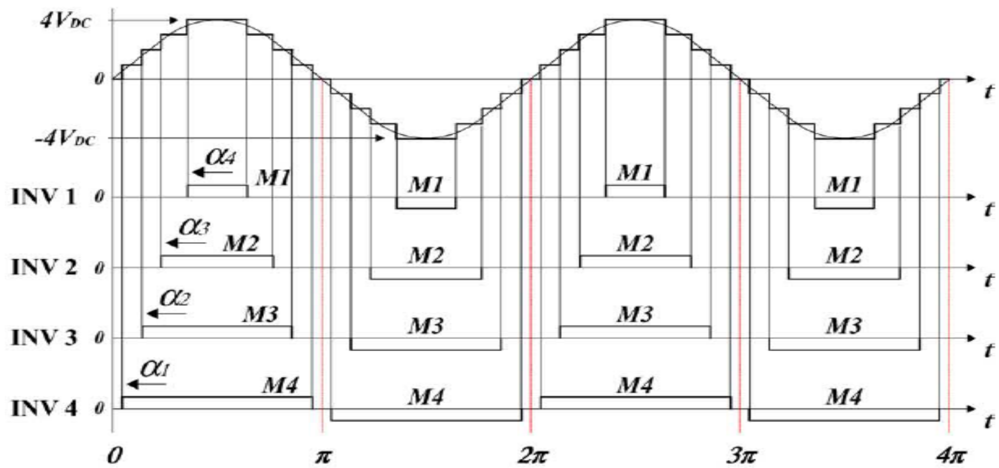


Fig. 4. CHML inverter switching pattern-swapping scheme [32].

PLL and then is used for reference voltage production. Vsd, Vsq obtained from their proportional elements are reduced $V_{ref,d}$, $V_{ref,a}$. Finally, they are taken to ABC reference. Then they go to the pulse generation block.

3.3. Multilevel Inverters Control

Multilevel inverters are largely divided into three configurations [36]: DCML inverters, FCML inverters, and CHML multilevel inverters. Among them, a cascaded H-bridge inverter with separate dc sources is useful for practical applications owing to the following advantages:

A modularized circuit layout and packaging is possible because each H-bridge cell has the same structure

It does not need extra clamping diodes or voltage balancing capacitors

It requires the reduced number of components to achieve the same number of output voltage levels among the conventional multilevel inverters.

Addition of H bridge cells, increases the voltage level. In Fig. 3 a nine-level cascaded inverter with four H bridge cells is shown. Its switching strategy is exhibited in Fig. 4.

But one of the CHML inverter defects is their need to a separate dc voltage for each H Bridge cells. Moreover, an instantaneous peak value of output voltage could not excess the sum of every individual input voltage source. If cascaded transformers were used in inverter structure, one dc voltage is needed (modified CHML inverter).

Fig. 5 shows a configuration of the modified CHML inverter. Owing to the cascaded transformers, it has isolation between an input dc source and output loads. Where the modified multilevel inverter employs the conventional step-pulse switching function depicted in Fig. 6.

The difference of magnetic flux changes the rating of cascaded transformers. This creates problems in the design of the transformer. Moreover, current rating of each full bridge cell becomes different. As a result, it is undesirable in practical applications.

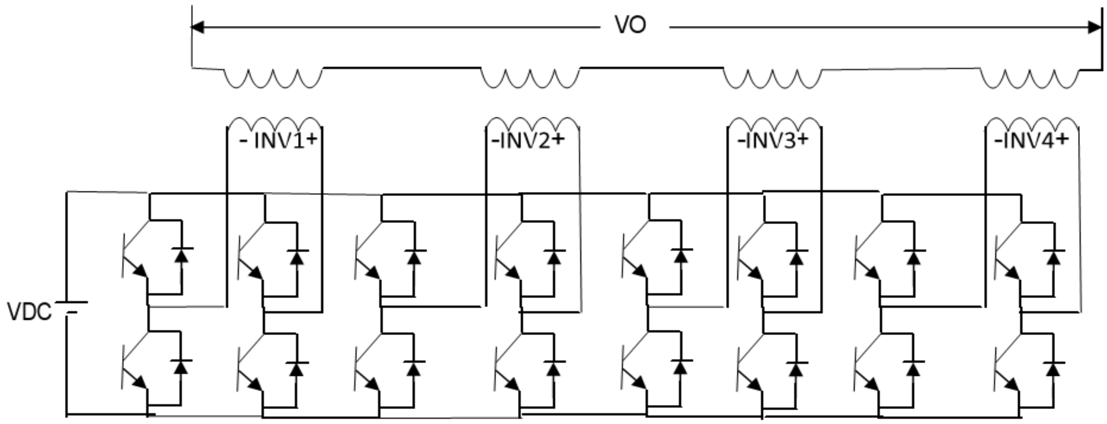


Fig. 5. Modified CHML inverter [32].

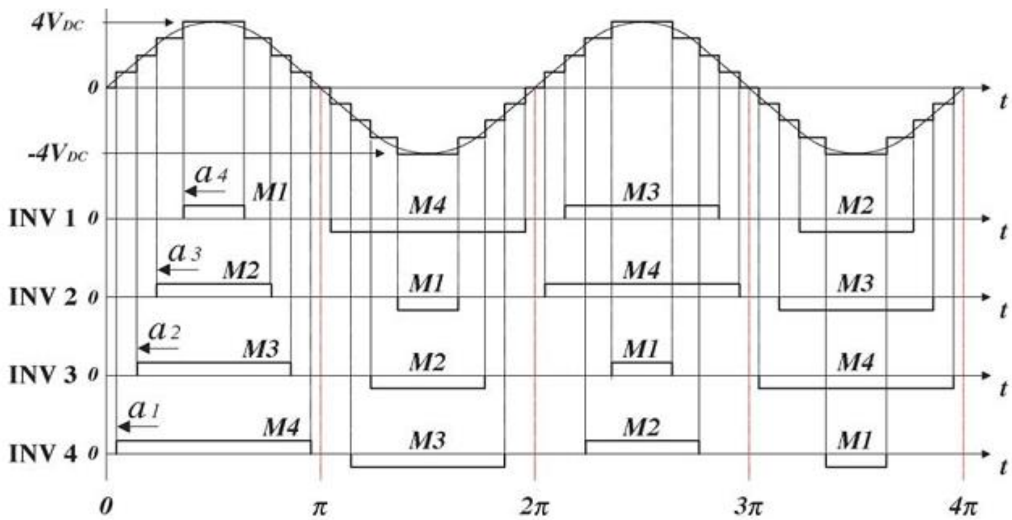


Fig. 6. Modified CHML inverter switching pattern-swapping scheme.

To solve this problem, a switching pattern-swapping scheme can be employed to equalize power transferred via each transformer. As shown in Fig. 7, it makes the transformer's voltage and current stresses the same and keeps an averaged magnetic flux imposed on each transformer balanced.

4. SIMULATION RESULTS

The network that is shown in Fig. 7, is used for problem simulation. The test system includes a 400V transmission line that the load is represented by a simple RL series equivalent rated at 400V, 125kW. The system configurations and parameter values are given in Table I, respectively.

Matlab software is utilized for simulation. The LC filter is used in this network. This filter is used to disturb the high frequency harmonics. Owing to presence of cascaded transformers in modified CHML inverter structure, injection transformers are not seen in Fig. 8.

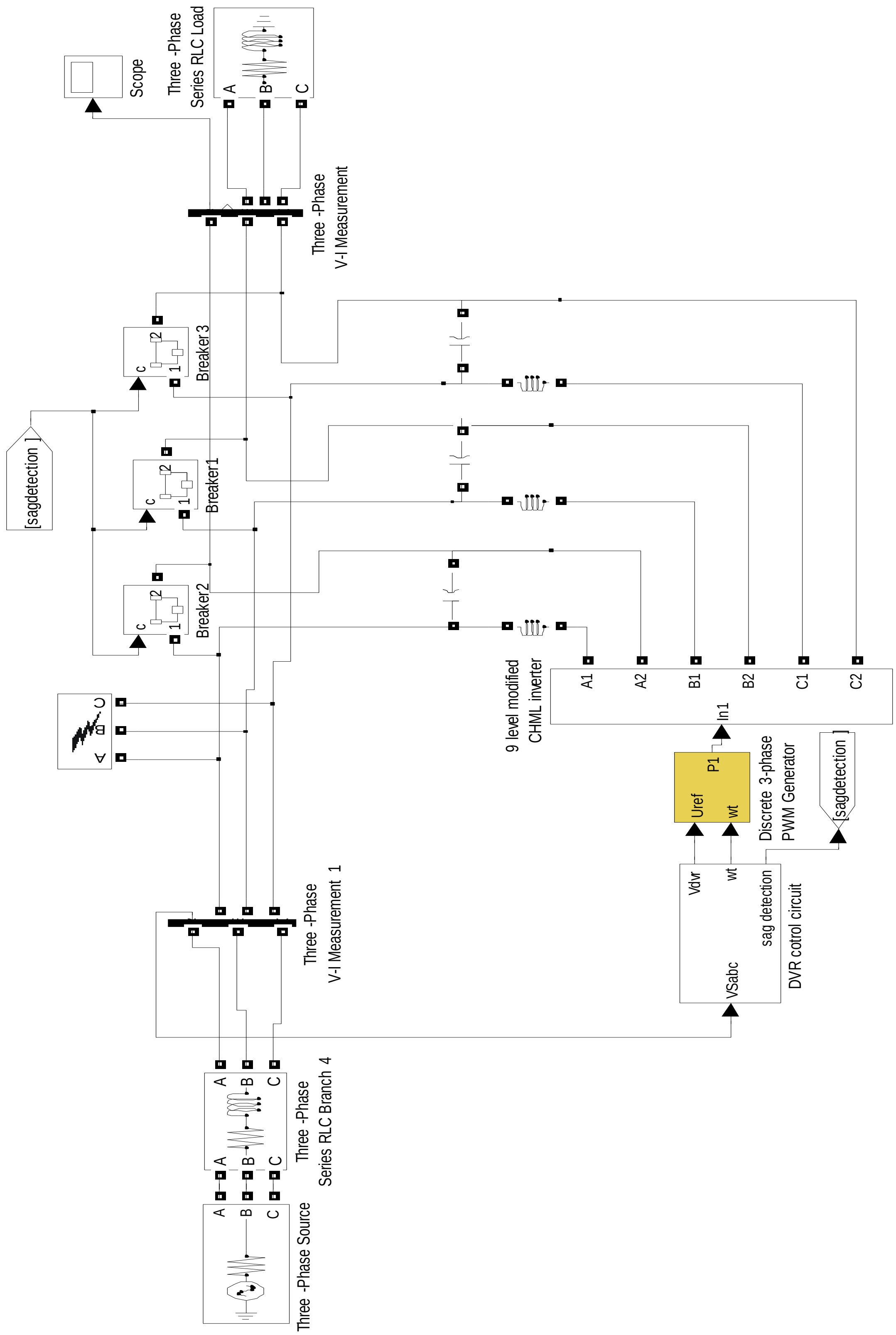
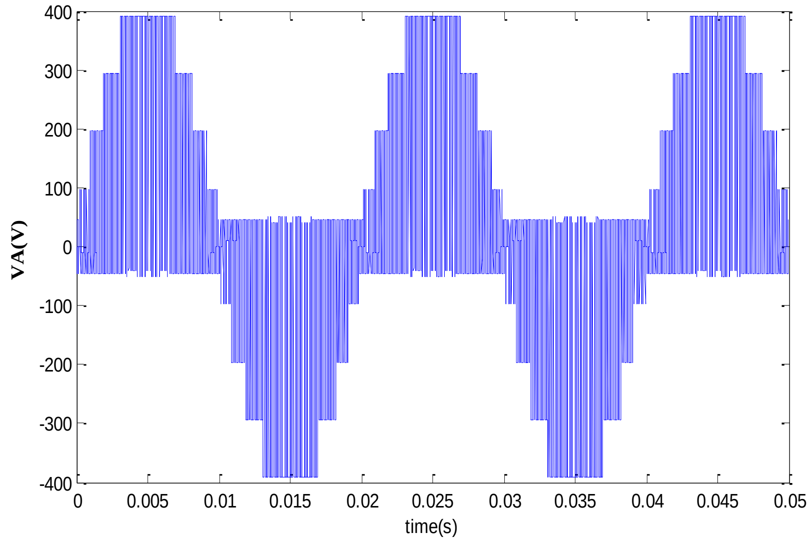


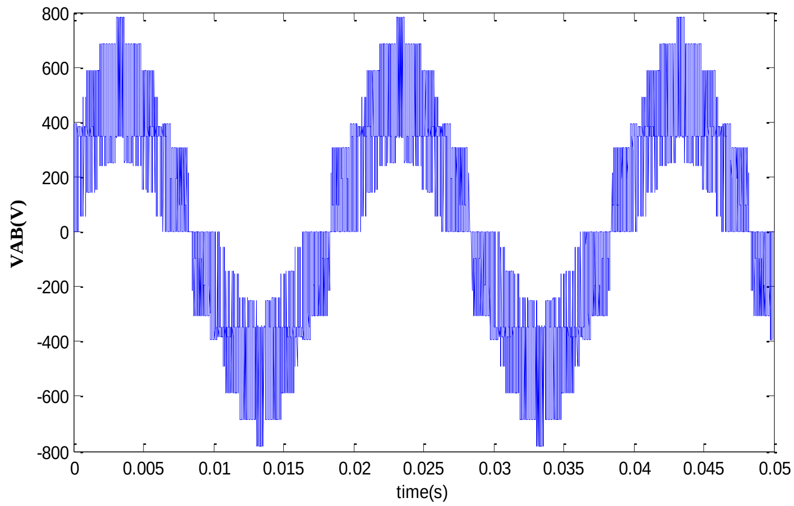
Fig. 7. Experimental DVR system setup.

Table 1. ***Simulation parameters [37].***

Phase to phase voltage source	400 Volt
Load power	125 kW
Power factor	0.8
Filter capacitor	30 μF
Filter inductor	2 mH
VDC	100 volt
Nominal frequency	50 Hz



(a)



(b)

Fig. 8. Nine-level modified CHML inverter.

DVR control circuit is exhibited in Fig. 9. The simulation parameters are depicted in Table. 1.

Nine-level modified CHML inverter outputs, before settling in DVR circuit is exhibited in Fig. 10. Fig. (10-a) is phase A voltage and Fig. (10-b) is phase A- phase B voltages.

For investigation of DVR performance, a three phase fault is created at 0.1 sec and is eliminated at 0.3 sec that is shown in Fig. 8. This fault generates 150 V voltage drop. When fault occurred, sag detection distinguishes it and disconnects the breakers. Then DVR is imported to the circuit. DVR is one of the good compensators.

Fig. 11 shows source voltage, injected voltage by DVR and compensated load voltage. In first simulation, fault was balanced.

For study DVR performance in unbalanced conditions, a 25 KW load that is sample R shunted by R-L load, is connected to phase A at 0.1 sec and is separated at 0.2 sec in Fig (11-a) its resulted voltage drop is depicted in phase A. Fig (11-b) shows the DVR injected voltage that consists of only one phase voltage. Fig. (11-c) also exhibit load voltage that is compensated very well. In this section frequency is 50Hz.

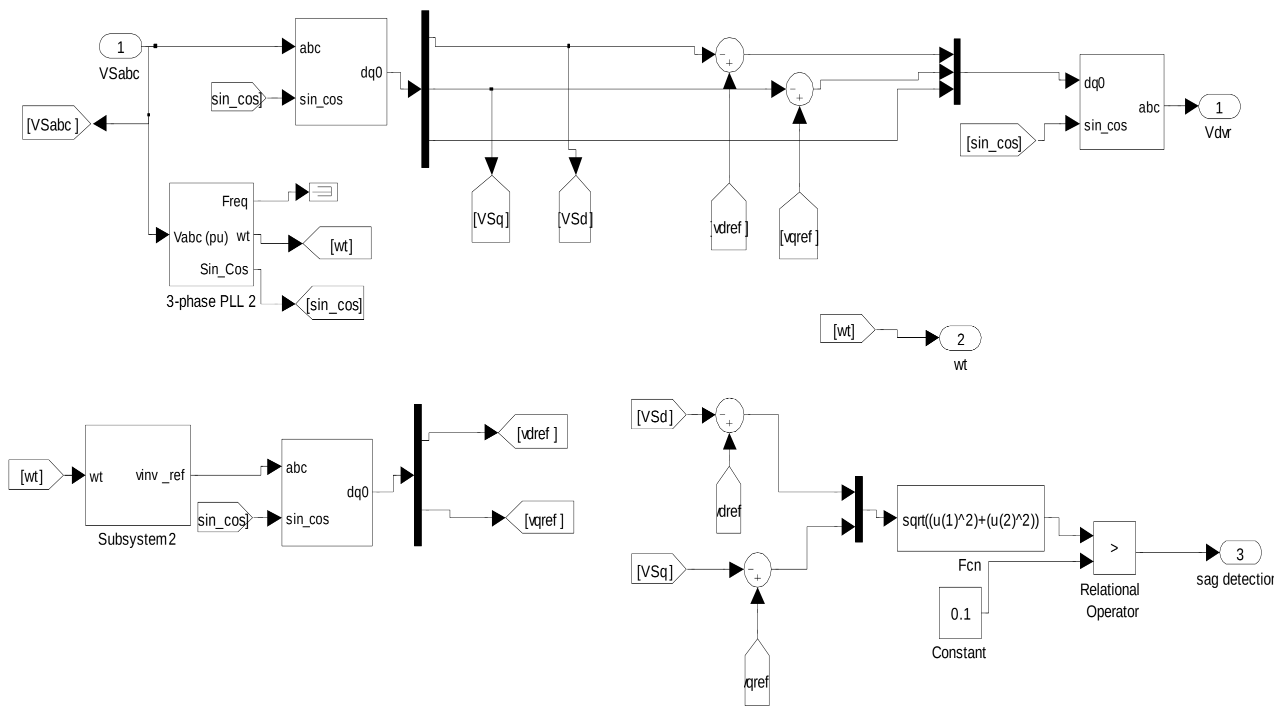
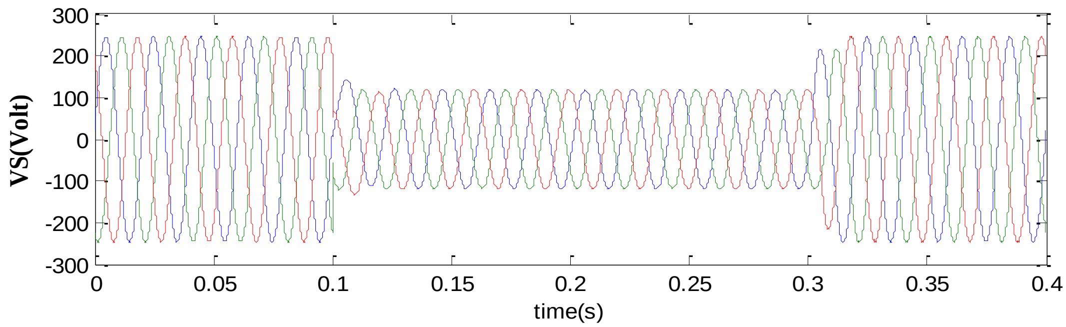
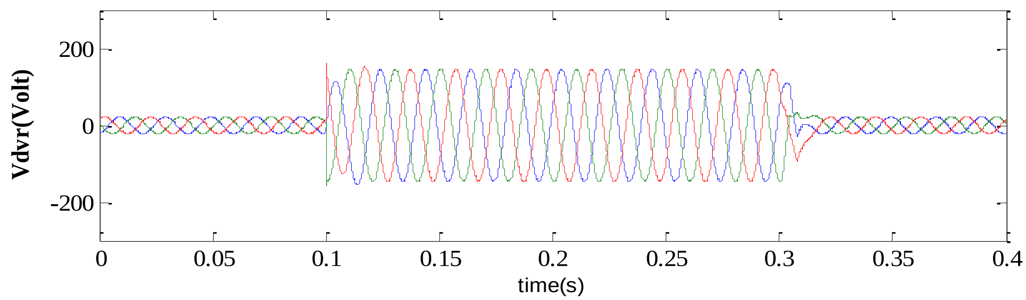


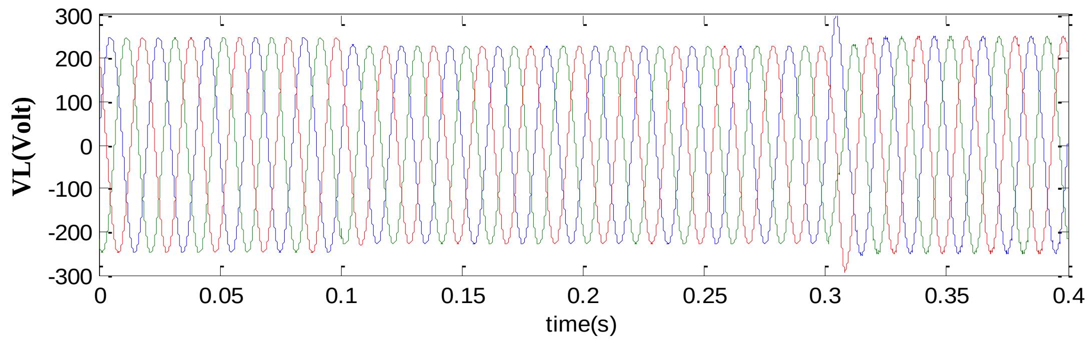
Fig.9. DVR control circuit.



(a) Source voltage

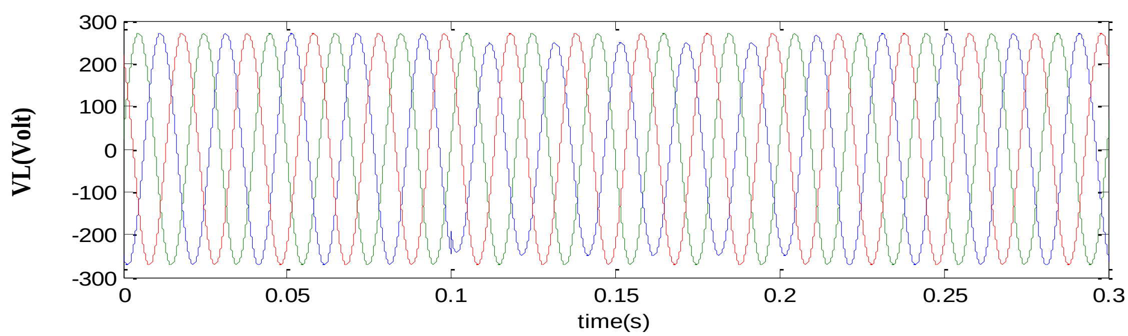


(b) DVR injected voltage



(c) Compensated load voltage

Fig. 10. Three phase fault.



(a) Source voltage

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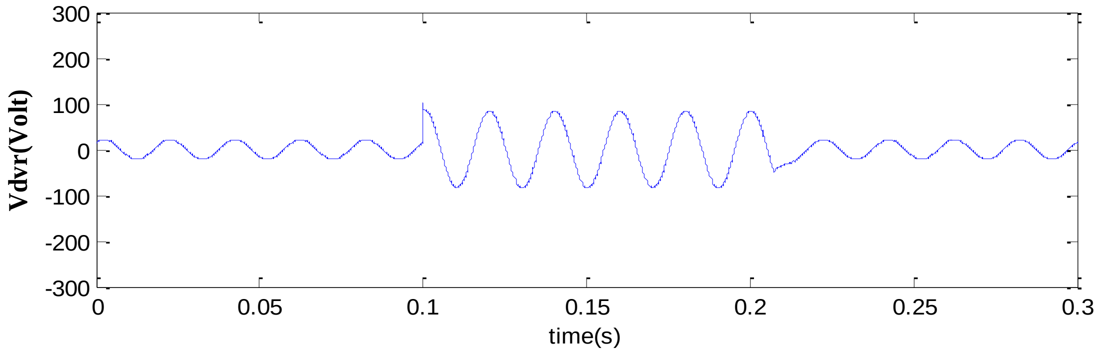
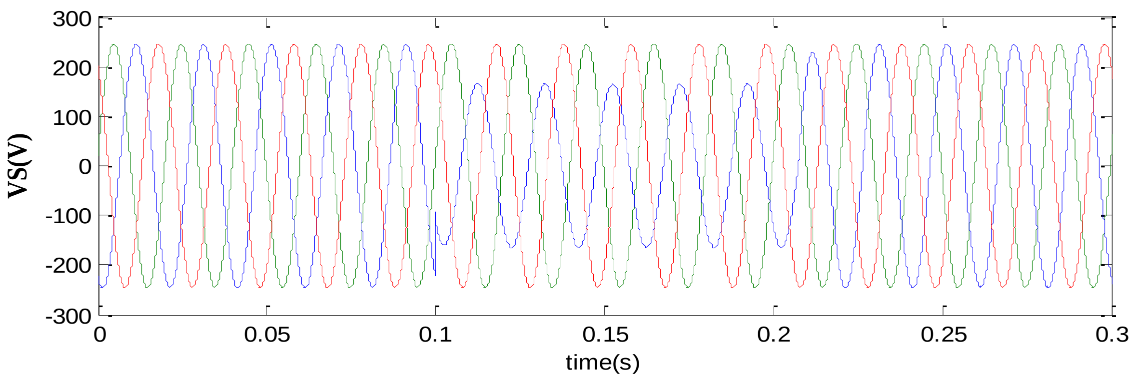


(b) DVR injected voltage



(c) Compensated load voltage

Fig. 11. Overload in phase A.

5. CONCLUSIONS

Dynamic voltage restorer is the most efficient and effective modern custom power device used in power distribution networks. It is connected in series and the impedances inserted lead to unwanted voltage drops and losses. In this paper, 9-level CHML inverter with cascaded transformers were used in DVR circuit. But to disturb magnetic harmonics of transformers, a new switching strategy was used. This kind of DVR performed very well for compensating voltage drop.

ABBREVIATIONS

DFACTS: distributed FACTS
DVR: dynamic voltage restorer
FACTS: flexible ac transmission systems
IPFC: interline power flow controller
SSSC: static synchronous series compensator
STATCOM: static synchronous compensator
TCSC: thyristor-controlled series capacitor
UPFC: unified power flow controller
UPQC: unified power quality compensator
UPS: uninterruptible power supply
PLL: phase locked loop

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