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Transformerless Dynamic Voltage Restorer for Medium Voltage Applications

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***Abstract*—Power quality is an important issue due to its impact on electricity suppliers, equipment manufactures and customers. In this paper a predictive voltage control scheme for the effective control of transformer less dynamic voltage restorer (TDVR) is discussed. This control scheme employs the discrete model of a voltage source inverter and a filter for the generation of the switching strategy of inverter switches. Predictive voltage control algorithm based TDVR utilizes the reference voltage effectively. And thus maintains sinusoidal load voltages during various voltage disturbances as well as load conditions. Moreover, this scheme does not require any linear controller or modulation technique.**

***Index Terms*— TDVR (Transformer less Dynamic Voltage Restorer), Predictive Voltage Control.**

I. INTRODUCTION

Power quality problems have received much attention recent years. It refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location in the power system. Power distribution systems, should provide their customers with an uninterrupted flow of energy with a smooth sinusoidal voltage at the contracted magnitude level and frequency. In practice, power systems, especially distribution systems, have numerous nonlinear loads, which significantly affect the quality of the power supply. As a result of these nonlinear loads, the purity of the supply waveform is lost in many places. This ends up producing many power quality problems. Voltage disturbances such as sag, swell, unbalance, and/or transients have adverse effects on sensitive loads [1], [2].

The dynamic voltage restorer (DVR), one of the custom power devices, has been utilized to protect sensitive loads from these voltage disturbances [3], [6]. The DVR injects a compensating voltage in series with the line through an injection transformer to maintain the load voltage at a desired value. However, several issues, namely, cost, weight, and losses related with the series injection transformer, make the application of conventional DVR undesirable at places like homes, offices etc.

To overcome these limitations of the conventional DVR, a transformer less DVR (TDVR) scheme with reduced cost, weight, size, and losses has been proposed [7], [8]. The TDVR satisfactorily mitigates the voltage disturbances and maintains a constant voltage at the load terminal.

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Here it presents a predictive voltage control scheme for TDVR to maintain load voltage at a constant value during voltage disturbance as well as under unbalanced and nonlinear loads. A detailed discrete-time state-space model of the TDVR compensated system is derived to predict the future values of the load voltage, which depends upon the sensed currents and voltages. A predictive control scheme has found applications in the control of power electronic converters such as single-phase and three phase VSIs, rectifiers, active power filters, uninterrupted power supplies, Dc-Dc converters, and motor drive [10][19]. They are mainly of three categories such as shunt connected distribution static compensator (DSTATCOM), series connected compensator like dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC) which is connected in both shunt and series with the ac mains.

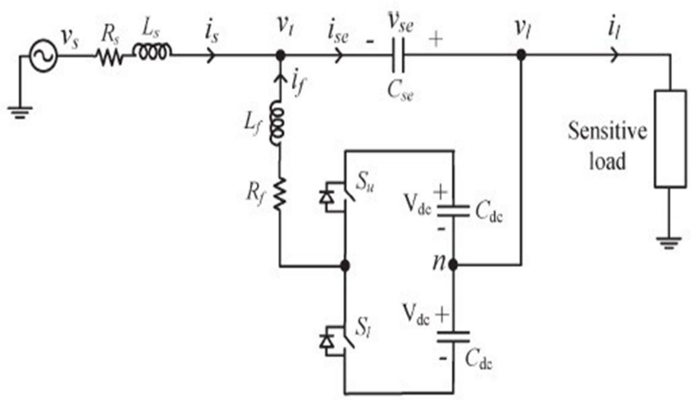


Fig. 1. The Single-phase TDVR equivalent circuit

A. Transformer less Dynamic Voltage Restorer

The main functions of the injection transformer include voltage boost and electrical isolation. Apart from its cost, it is bulky and it contributes toward the restorer losses [9, lo]. Even judiciously designed, there can still be problems such as those pertaining to the saturation and inrush currents associated with the transformer magnetization phenomenon [9].

Hence, there is great incentive to investigate whether a DVR can be designed and operated without the transformer, such that the reliability and effectiveness of this restoration scheme can be enhanced and concurrently the cost of the restoration system can be reduced [lo].

The source voltage is represented by V_s. The resistance and inductance of the source are R_s and L_s, respectively. The source, load, filter, and series capacitor currents are represented by i_s, i_l, i_f, and i_{se}, respectively. The source is supplying to an unbalanced nonlinear load.

The TDVR consists of a half bridge VSI, an output filter (L_f and C_{se}), and neutral point clamped dc capacitors. The voltage across the filter capacitor (V_{se}) connected in series with the line is controlled to maintain the desired voltage at the load point. The main objective is to design and implement a transformer less DVR for medium power applications using the predictive voltage control strategy.

The equivalent circuit of TDVR shown in Fig. 3 is a second order circuit. In this circuit, the current through the filter inductor and the voltage across the series capacitor are taken as the state variables. The dynamics of this system are given by the following differential equations:

$$\frac{di_f}{dt} = -\frac{R_f}{L_f} i_f + \frac{1}{L_f} V_{se} + \frac{1}{L_f} V_{inv} \qquad (1)$$

Considering i_f and v_{se} *as* state variables and v_{inv} and i_s as input variables, the state-space continuous-time equation is given as:

$$X' = Ax + Bz \qquad (2)$$

Where $x = [v_{se} i_f]^t$ *and* $z = [v_{inv} i_s]^t$. Also, in (3)

Features	Conventional DVR (CDVR)	Transformerless DVR (TDVR)
Voltage regulation during normal operation	Voltage drop across DVR terminals due to transformer impedance, typically >5%.	Voltage drop is caused by on state voltage drop of switching components, normally negligible.
Losses of normal operation of distribution system	Transformer losses and conduction losses of inverter switches. Transformer losses can be a few percent.	Only negligible conduction losses of switching devices.
Losses during voltage sag period	Transformer and inverter switching losses.	Only inverter switching losses.
Size	Bulky.	Much smaller without transformer.
Cost	Expensive.	Less expensive as series transformer is not needed.
Reliability	As the number of switching components is identical, level of reliability can be considered the same for inverter. By excluding the injection transformer, problems related to the transformer are avoided. Thus the reliability of TDVR is higher than CDVR.	

Fig. 2. Comparison of TDVR and CDVR

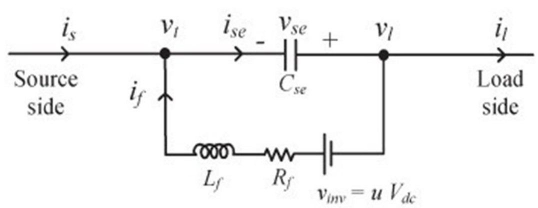


Fig. 3. The equivalent circuit of the TDVR

II. EXISTING SYSTEM DESCRIPTION

The equivalent circuit of the TDVR at any time of operation is shown in Fig. 3. The term u is the switching variable. The upper and lower switches, S_u and S_l, respectively, are operated in a complementary way, i.e., if the upper switch is ON (u = 1) then the lower switch will be OFF (u = 1) at any time instant and vice versa. A voltage of V_{dc} is maintained across each of the dc-link capacitor C_{dc}. A voltage of V_{se} is generated across the series capacitor by the proper operation of the VSI to maintain the load voltage sinusoidal with constant magnitude.

And as a modification in this paper a single phase abc to dq transform is proposed, which is easy to be implemented for the generation of series estimated voltage. A single-phase system can directly convert into $\alpha\beta$ frame without any matrix transformation. An imaginary variable obtained by shifting the original signal (voltage/current) by 90 degrees and thus the original signal and imaginary signal represent the load current in $\alpha\beta$ co-ordinates.

$$\frac{dV_{se}}{dt} = -\frac{1}{C_{se}} i_s - \frac{1}{C_{se}} i_r \qquad (3)$$

The discrete time state space form of (3) at the (k +1)th sampling instant with a sampling time of T_d.

$$x(k+1) = Gx(k) + Hz(k) \quad (4)$$

And finally, the dynamics of the considered system in the discrete-time state-space domain is constructed as follows.

While deriving the discrete-time model of the system it was assumed that during two subsequent sampling instants the signal remains constant. Therefore the above expression can be differentiated with respect to VSI voltage.

$$G = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = e^{AT_d} \approx I + AT_d + \frac{A^2 {T_d}^2}{2}$$

$$\approx \begin{bmatrix} 1 - \frac{R_f T_d}{L_f} - \frac{{T_d}^2}{2L_f}\left[\frac{1}{C_{se}} - \frac{{R_f}^2}{L_f}\right] & -\frac{T_d}{L_f} + \frac{R_f {T_d}^2}{2{L_f}^2} \\ \frac{T_d}{C_{se}} - \frac{R_f {T_d}^2}{2{L_f}^2 C_{se}} & 1 - \frac{{T_d}^2}{2L_f C_{se}} \end{bmatrix} \quad (5)$$

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \int_0^{T_d} e^{A\lambda} B d\lambda \approx \int_0^{T_d} (I + A\lambda) B d\lambda$$

$$\approx \begin{bmatrix} \frac{{T_d}^2}{2L_f C_{se}} & \frac{V_{dc}}{L_f}\left(T_d - \frac{R_f {T_d}^2}{L_f}\right) \\ -\frac{T_d}{C_{se}} & \frac{{T_d}^2 V_{dc}}{2L_f C_{se}} \end{bmatrix} \quad (6)$$

i.e, by solving the matrices.

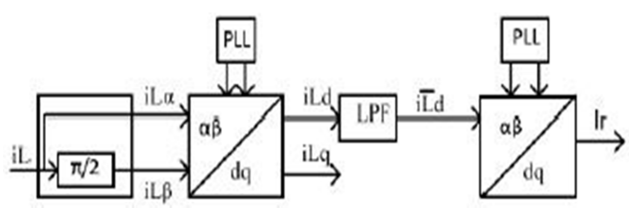
$$i_f(k+1) = g_{11} i_f(k) + g_{12} v_{se}(k) + h_{11} v_{inv}(k) + h_{12} i_s(k) \quad (7)$$

$$v_{se}(k+1) = g_{21} i_f(k) + g_{22} v_{se}(k) + h_{21} v_{inv}(k) + h_{22} i_s(k) \quad (8)$$

The predictive voltage control scheme makes the VSI to operate such that the load voltage is maintained constant and sinusoidal at any operating conditions. The error between the reference injected voltage of series capacitor and actual injected voltage have to be minimized. A cost function based on the active and reactive power control, minimization of switching frequency, dc link voltage balancing etc is designed.

The series capacitor of the TDVR is connected between the PCC and load point. The main objective of the TDVR is to inject three-phase voltages such that the load voltages remain balanced and sinusoidal with a constant magnitude even during voltage disturbances.

B. Single Phase Abc to Dq Transform



A single-phase system can directly convert into frame without any matrix transformation. An imaginary variable obtained by shifting the original signal (voltage/current) by 90 degrees and thus the original signal and imaginary signal represent the load current in $\alpha\beta$ co-ordinates. Here we are using the DC component for the generation of reference current hence it is called indirect method. The load requires only fundamental active part of the source current.

III. SIMULATION AND RESULTS

The circuit is simulated using MATLAB is shown in fig. 4. The performance of a transformerless DVR is analyzed. A source voltage of 230 V_{rms} is considered, and the TDVR reference voltage is also set at 230 V_{rms}. The sampling frequency is set to 20 kHz. The value of the filter inductor needs to be chosen based on criterion such as switching frequency, harmonic level, and filter size [2], [4]. A small inductor reduces the overall filter described in [22] is used for synchronization. The angle is the load angle which is used to maintain the power balance at the load point in addition to maintaining the dc-bus voltage constant. It is computed using a proportional-integral (PI) controller which ensures that the load power is taken from the source by maintaining the VSI dc-link voltage constant.

The value of the filter inductor needs to be chosen based on criterion such as switching frequency, harmonic level, and filter size [2], [4]. A small inductor reduces the overall filter size; however, the switching frequency will be high, losses in the inverter will be more, and the load voltage will also have significantly high switching frequency components. With a relatively moderate size filter inductor, the filter size increases, but the switching frequency will be low, inverter losses will reduce, and the load voltage will have lesser switching frequency components. Taking these considerations into account, the value of the filter inductor should be chosen as a tradeoff between the constraints like inverter switching frequency, harmonic level in the load voltage, and size of the filter [2], [4].

A 5-mH inductor is chosen for filter applications. With this filter, the performance of TDVR for voltage sag of 30% is shown in Fig. 5. In this case, it can be seen that the load voltage is maintained constant and sinusoidal throughout the operation. This confirms the effectiveness of the proposed scheme. However, the load voltage contains a significant switching frequency component along with having a switching frequency of 20 kHz.

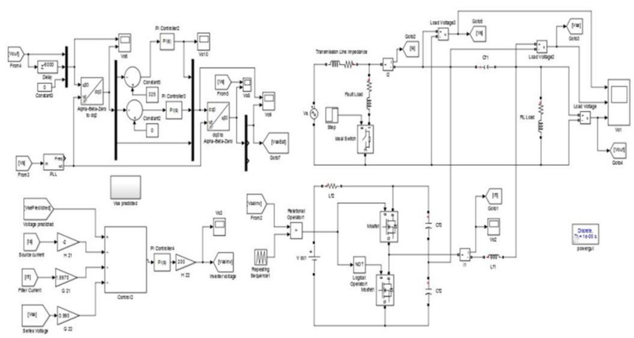


Fig. 4. Simulation diagram of Predictive voltage controlled Transformerless Dynamic Voltage Restorer

With a relatively moderate size filter inductor, the filter size increases, but the switching frequency will be low, inverter losses will reduce, and the load voltage will have lesser switching frequency components. Taking these considerations into account, the value of the filter inductor should be chosen as a tradeoff between the constraints like inverter switching frequency, harmonic level in the load voltage, and size of the filter [2], [4].

To reduce the switching frequency and the harmonic level in load voltage, a moderate size inductor of 5 mH is used as filter inductance. RL-type nonlinear load (500W) is considered. For analyzing sag a fault is applied to the system by switching a nonlinear load (1000W) is applied. Whereas for analyzing swell a variable voltage controller is applied so as to provide a large increase in the source voltage. After simulation it is observed that the load voltage waveform is smooth during voltage disturbance (i.e., during normal to sag and vice versa).The load voltage is maintained at its reference value throughout the operation, whereas the load current is drawn as per the requirement.

The result confirms that the load voltage waveform has significantly lower switching frequency component and the VSI switching frequency is significantly reduced as compared to the result with the 5-mH filter inductance. Also, the load voltage waveform is smooth during voltage disturbance (i.e., during normal to sag and vice versa). Furthermore, Fig.6 shows the performance of the predictive control scheme during a voltage swell of 30%. Again, the load voltage is sinusoidal.

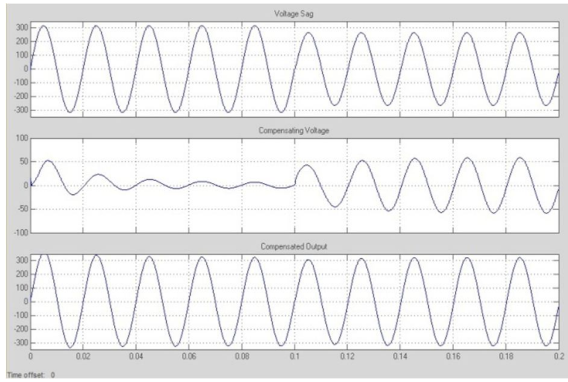


Fig.5. Waveform of transformerless DVR during Sag

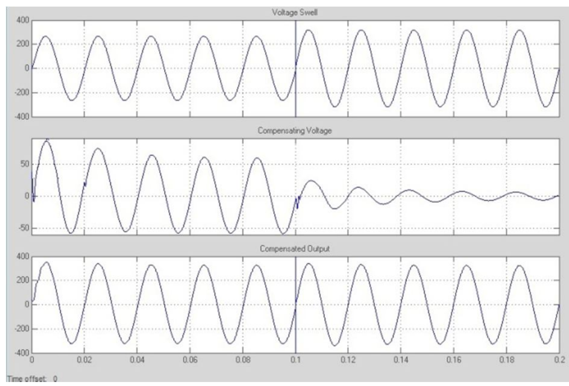


Fig.6. Waveform of transformerless DVR during Swell

IV. CONCLUSION

The DVR without the injection transformer shows that by introducing separate DC-link energy storage, the proposed transformerless DVR can satisfactorily mitigate the voltage- sag problems. The design is promising as it indicates a less costly restorer of a more compact structure.

The Predictive voltage control of TDVR can be implemented for the better performance and control. This scheme will provide good voltage tracking and dynamic performance without utilizing any linear controller or modulation technique.

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