Simple Design Criteria of Injection Transformer for the Dynamic Voltage Restorer

P. Boonchiam and N. Mithulananthan

Abstract— *This paper presents the design strategy of injection transformer for the dynamic voltage restorer. The injection transformer used in the dynamic voltage restorer plays a crucial role in ensuring the maximum reliability and effectiveness of the restoration scheme. The functional relationship between the transformer and the other components constituting the dynamic voltage restorer and external distribution system is analyzed. The design strategy based on investigation leading to a cost-effective restoration is then proposed.*

***Keywords*— Transformer, DVR**.

1. INTRODUCTION

Distribution transformers are fundamental components in power distribution systems. They are relatively inexpensive, highly reliable, and fairly efficient. However, they have some disadvantages such as heavy weight, large size, sensitivity to harmonics, voltage drop under load, (required) protection from system disruptions and overload, protection of the system from problems arising at or beyond the transformer and environmental concerns regarding mineral oil. These disadvantages are becoming increasingly important as power quality becomes more of a concern. In this case, power electronic based transformer is a good option for solving above problems.

By injecting voltages in series, the dynamic voltage restorer (DVR) has been proven to be effective in alleviating voltage sag-related problems. The injected voltages are introduced into the distribution system through an injection transformer connected in series with the distribution feeder as shown in Fig. 1. It has been recognized that in order to guarantee the maximum reliability and effectiveness of this restoration scheme.

This paper is intended to address some of these issues and proposes a method on how to cost-effectively incorporate such a transformer into the restorer. The determination of the following parameters of the transformer are detailed in this paper: the MVA rating, The short-circuit impedance, The primary winding voltage and current ratings, The turn-ratio which, in turn, determines the secondary winding voltage and current ratings

Investigation results show that the determination of the above parameters is dependent of the following system characteristics: the MVA rating of the sensitive load to be protected, The maximum allowable voltage drop across the transformer, The characteristics of the expected voltage sags to be compensated for, The design of the harmonic filter system, the selection of the switching devices, The energy storage capacity and the voltage restoration and control strategy.

2. DYNAMIC VOLTAGE RESTORER

A DVR is a custom power device capable of protecting sensitive loads against the voltage variations or disturbances. A DVR is a forced commutated voltage source converter (VSC) that injects a dynamically controlled voltage in series with the supply voltage through three single-phase transformers for correcting the load voltage. When the injected voltage is in phase with the supply voltage, the desired voltage correction can be achieved with a minimum voltage injection but it may required a considerable amount of active power injection into the system [3]. When the injected voltage leads the supply voltage, the same correction can be made with a lower value of power injection. When the power injection by the DVR is minimized, the same energy storage can be used for a longer period. Such an operation requires careful determination of injected voltage magnitude and angle, however.

Fig. 2 shows the schematically diagram of a typical DVR used for voltage correction. When the supply voltage Vs changes, the DVR injects a voltage Vi in such a way that the desired load voltage magnitude can be maintained.

Fig. 1. Installation of injection transformer in power distribution system.

P. Boonchiam is with Rajamangala University of Technology Thanyaburi and Asian Institute of Technology. He is now with the Department of Electrical Engineering. E-mail: paisan@rmutt.ac.th.

N. Mithulananthan is with Energy Field of Study, Asian Institute of Technology. E-mail: mithulan@ait.ac.th.

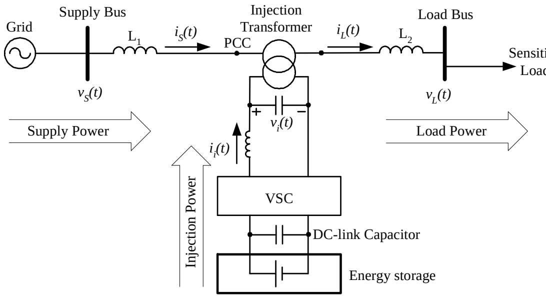

Fig. 2 Schematic diagram of a typical DVR.

DVR is simply a VSC that produces an ac output voltage and injects in series with the supply voltage through a injection transformer. To correct a given voltage sag, not only voltage but also active and/or reactive power injections are needed. A DVR must be able to react very fast on different kinds of voltage sags. The amplitude of the load-side voltage must be restored and for most loads large phase jumps must be avoided. Especially, the correct compensation of single phase voltage sags is a major issue. Control of a DVR can be realized by using dqn-components.

As already mentioned different strategies can be used to achieve at least one aspect of an optimized control. The three basic strategies are the Pre-Sag Compensation, the In-Phase-Compensation and the Energy-optimized Compensation. To avoid a loss of power supply, the amplitude of the load voltage has to be restored by the DVR. Therefore, different strategies can be used to achieve this goal.

A. Pre-sag Compensation

The standard solution for compensating voltage sags is to re-establish the exact voltage before the sag. Therefore, the amplitude and the phase of the voltage before the sag have to be exactly restored. The resulting vector is shown in the following Figure 3. This compensation leads to the lowest distortions at the load, because the voltage at the load is not changed due to the sag. For this strategy, a PLL will be synchronized with the load voltage. As soon as the failure occurs, the PLL will be locked and therefore the phase angle can be restored. Depending on the phase of the new grid voltage, the DVR has to deliver higher voltage amplitude than needed in order to restore the correct voltage magnitude. Therefore, the system has to be designed for a higher maximum voltage (VDVR) and less energy from the DC-Link can be used.

B. In-Phase Compensation

As already mentioned, the Pre-Sag Compensation does not lead to a minimized voltage amplitude. This can be realized with the In-Phase Strategy, which is designed to control the DVR with a minimum output voltage. In Fig. 4, the voltages for this strategy are depicted. In contrast to the Pre-Sag version, the voltage is now compensated in phase to the grid voltage after the sag. Hence, the needed voltage amplitude is minimized.

In most cases, a voltage sag leads to a phase jump, therefore the distortions due to phase changes are not minimized. As a consequence, a phase jump will occur at the load, leading to transient currents. If a sensible load is secured, then the In-Phase compensation cannot be used, because it would lead to a loss of power supply. To realize this strategy, the PLL has to be synchronized to the grid voltage itself and therefore will not be locked during the compensation.

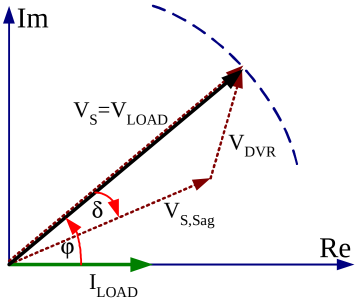

Fig.3. Pre-Sag Compensation.

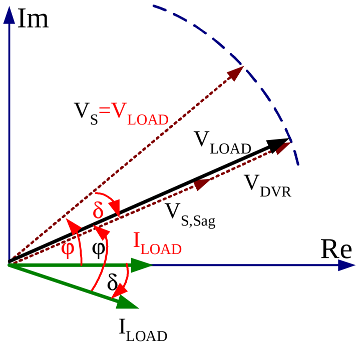

Fig.4. In-Phase Compensation.

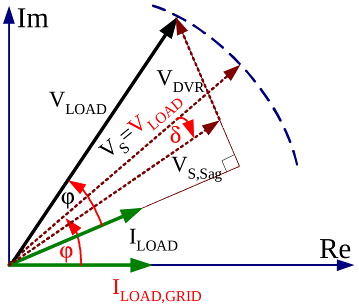

Fig.5. Energy Minimized Compensation.

C. Energy Optimized Compensation

Another existing control strategy is to use as much reactive power as possible to compensate the sag. So, the DVR voltage is controlled in such a way that the load current is in phase with the grid voltage after the sag. As long as the voltage sag is quite shallow, it is possible to compensate a sag with pure reactive power and therefore the compensation time is not limited. In Fig.5 the voltages for the energy optimized compensation are depicted. Beside the enormous advantage of not requiring active power, this strategy has in most cases two major disadvantages. On the one hand, the phase distortions and on the other hand the needed voltage amplitude are quite high. Furthermore, the compensation with pure reactive power is only possible for shallow sags. If a deep sag occurs, active power is needed and in an extreme case it becomes equal to the Pre-Sag Compensation.

3. VOLTAGE RATING OF PRIMARY WINDING

To be cost-effective, partial boosting is often considered when designing a DVR. This means that a voltage injection limit will normally be placed on the injection transformer. Thus the voltage sag characteristics, the control algorithm and the headroom provided in the restorer will determine the resulting output voltage waveform. In other words, in selecting the injection transformer, the determination of its expected maximum voltage output is of special significance, both economically and technically. Factors that should be taken into consideration when deciding on the primary-winding rated voltage of the injection transformer will be detailed in the following context.

- Sag magnitude specification
- Voltage sag characteristics
- Progressive phase-advance voltage restoration
- Filtering considerations

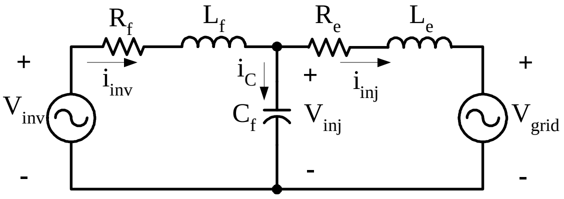

Fig.6. Equivalent circuit of the design of DVR.

4. 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. This is related to the placements of the filtering systems.

Inverter-side filtering system

Line-side filtering system

5. TURNS-RATIO SELECTION AND SHORT-CIRCUIT IMPEDANCE CONSIDERATION

The selection of the transformer secondary voltage and current ratings and its turns-ratio are interrelated. In this paper, the determination of the ratings takes into account the selection of the switching devices. To minimize the cost of the DVR, a heuristic method is proposed: 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 blocking voltage of the switching devices can then be readily determined. Continue adjusting the turns-ratio until commercially available and switching devices can be obtained. The procedure is given in [3]

The short-circuit impedance will affect the fault current through the transformer should a short-circuit occur on the load side. The 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. 6 is used, the effect of the filtering system on the voltage drop must be considered.

6. SIMULATION RESULTS

To illustrate a typical response of injection transformer of DVR with the proposed control strategy, a simple 50 Hz power distribution system with a sensitive load as shown in Fig. 2 is considered. The system data and DVR parameters are given in Appendix. The performance of injection transformer of DVR with vector control strategy is shown in Fig. 7 for balanced voltage sag due to a three phase fault that was initiated at 0.2 sec. and lasted for 0.05 sec as presented in the supply voltage graph. The load voltage and the injected voltage by DVR are also shown in Fig. 7. As can be seen from the figure, the proposed control strategy is able to drive the DVR to inject the appropriate three phase voltage component with correct phase to remove the supply voltage anomalies due to three phase fault. It was observed that during the normal operation the DVR is not functioning as expected. It quickly injects necessary voltage components to smoothen the load voltage upon detecting voltage sag. Similar performance is observed for an unbalanced voltage sag case as well.

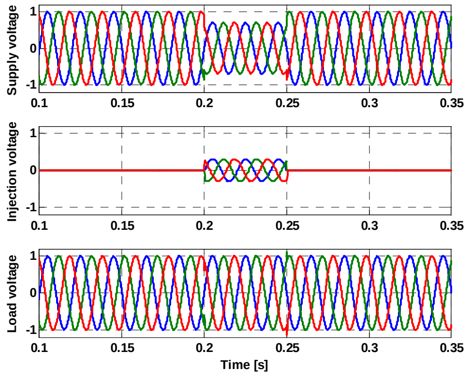

Fig. 7 Injection Transformer response to balanced voltage sag.

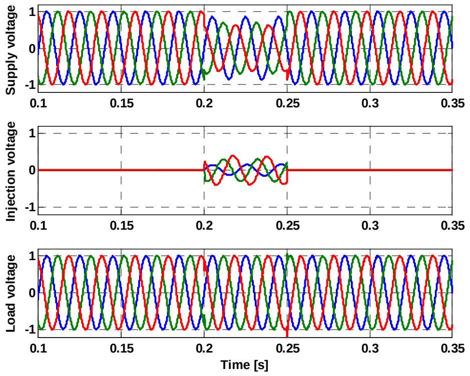

Fig. 8. Injection Transformer response to unbalanced voltage sag.

Figure 8 shows the performance of injection transformer of DVR control for unbalanced voltage sag created by double line fault in the system. As depicted in supply voltage the fault was initiated at 0.2 sec and it was cleared at 0.25 sec. As shown in Fig. 8, injection transformer of DVR with the proposed control strategy is quick in injecting the required unbalanced voltage component for correcting the load voltage and keeps it at nominal value.

7. CONCLUSION

The analysis shown in the paper elaborates on the relationship between the injection transformer and the other components which constitute the DVR and the distribution system. For the DVR designer, the design procedure can be adopted as a useful reference leading to a cost-effective DVR. For the DVR end-users, a better understanding of the crucial role plays by the injection transformer will surely facilitate the application of the new technology, leading to the production of high quality power in the electric utility industry.

APPENDIX

The system parameters, used in this paper, are given in Table below.

Nominal frequency f = 50 Hz	Switching frequency fsw = 400Hz
Sampling frequency fs = 5 kHz	Carrier frequency fc = 1200 Hz
Load parameters	Filter parameters
VLoad = 22 kV Sload = 1 MVA Power Factor = 0.9	Lf = 2.5 mH Cf = 800 μF Rf = 0.1 Ω

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