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Design and Testing of an Injection Transformer for a Dynamic Voltage Restorer (DVR)

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Abstract. The paper deals with a scaled model of a dynamic voltage restorer implemented in laboratory environment and it is focused on a series-connected injection transformer. A simplified design of the transformer and transformer tests are presented. The obtained results are further compared with simulation calculation.

Keywords: injection transformer, DVR, voltage sag, compensation, FACTS, power quality.

1. Introduction

The most severe power quality problems are voltage sags, swells, interruptions, harmonics and flickers. Failures due to such disturbances cause a huge impact on production cost. Especially, modern industrial equipment is more susceptible to power quality problems. They are, for example, computers or other electronics damage, lights dim and flickers, loss of synchronization of processing equipment, motors or other process equipment malfunctions, transformers and cables overheating, problems with power factor correction equipment, noise interference to telecommunication lines and many more [1].

A voltage sag means that the required energy is not being delivered to the load and this can have serious consequences depending on the type of load involved.

One of the possibilities for power quality and system stability improvement is to introduce FACTS devices. FACTS controllers are able to control and regulate one or more key parameters, such as current, voltage, active, reactive power, frequency or phase angle. According to [2], FACTS can be divided into four basic types – series connected, shunt connected, combined series-series and combined series-shunt controllers. The main disadvantage of implementing FACTS is a very high price of these devices and economic requirements.

1.1. Dynamic Voltage Restorer

Dynamic Voltage Restorer (DVR) belongs to series connected FACTS controllers. The primary function of a DVR is to compensate voltage sags and swells, but it can also perform tasks such as harmonics elimination, reduction of voltage transients and fault current limitation [3]. DVR is usually installed between a source and a critical load that should be protected. Even the shortest voltage sag can cause serious equipment damage, interruption of production cycles and financial losses. In general, a DVR consists of three parts (Fig. 1.):

- measuring unit,
- control unit,
- power circuit.

The measuring unit provides voltage and current measurements. The outputs are voltage and current analog signals (u, i), which enter the control unit. The control unit converts these signals to their digital representation using A/D converter so that they can be processed by a microcontroller or a DSP – digital signal processor. The next part is a voltage sags detection algorithm followed by a calculation of the compensating voltage U_{com}, which is the voltage needed to be injected into the system in order to maintain the load side voltage in rated values. The power section consists of a voltage source converter (VSC) equipped with a LC filter to smooth the output voltage, a DC energy storage and an injection transformer (TR) – booster.

The basic principle of DVR function is to inject or draw the compensating voltage U_{inj} to or from the supply voltage U_s in order to mitigate voltage sags or swells on the load side U_{load}. At every moment the control algorithm compares desired voltage and actual measured voltage. The difference between these two signals is considered as a compensating voltage U_{com} (control) and U_{inj} (power circuit). U_{com} is a digital input for a pulse width modulation (PWM) to control the voltage source converter. The VSC converts DC energy stored in an energy storage device (such as power supply, batteries or supercapacitors) to inject AC voltage that is to be superimposed to the source voltage using a transformer. DVR power output depends on the amount of energy that can be stored in the energy storage unit.

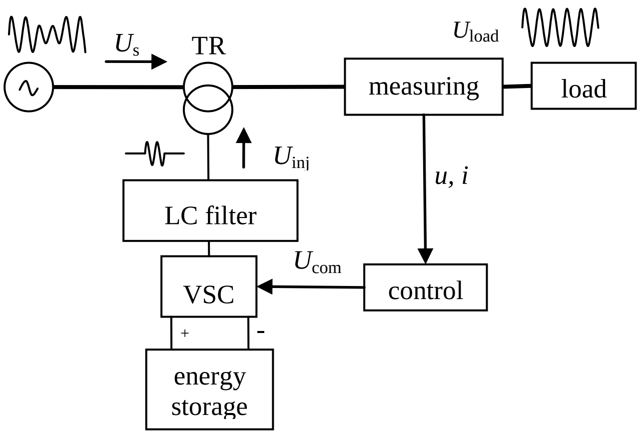

Fig. 1. Simplified scheme of a DVR

DVRs are usually installed to protect large consumers with the sensitive technologies and devices (2 MVA or more) connected at distribution level [7]. This paper describes a DVR scaled model designed and implemented in laboratory environment. The DVR is a single-phase model, it is designed for 22 kV (medium voltage) power line model and its parameters are: rated load voltage 127 V, current 1 A, power 127 VA and frequency 50 Hz. The DC voltage of the energy storage is 48 V. The DVR model is able to compensate sags with the maximum depth 77 % of rated voltage.

2. Injection Transformer

The injection transformer is connected in series with the line. When a sag occurs the injected voltage is added to the source voltage through the transformer. The operation of DVR has an impact on the phase shift and voltage drop, which depend on the transformer parameters [4]. A detailed procedure of the injection transformer design is presented in [5].

2.1. Transformer Design and Parameters

At the start of compensation, the magnetic flux and current in the coil start at zero and gradually increase. It means that the transformer flux is approximately twice the maximum value of the normal flux [7], [8]. This causes an inrush current in transformer and that requires the transformer to be rated two times larger than DVR. Thus, the transformer is large and expensive. The required parameters of an injection transformer for DVR laboratory model are:

- single phase, shell-type core,
- frequency - 50 Hz,
- rated power - 240 VA,
- primary winding - rated 240 V, 1 A (operating 120 V, 1 A),
- secondary winding - rated 60 V, 4 A (operating 30 V, 4 A).

The designed transformer is depicted at Fig. 2. DVR is in standby state, while the inverter side of series transformer is in short-circuit operation. That is when both of the switching devices on upper arms (or lower arms) of the inverter conduct simultaneously, and no voltage vector is injected into system. In this case, only transformer leakage reactance exists in circuit, since injected voltage is zero. During injection state, VSC generates compensating voltage. Injection transformer contributes to the elimination of the harmonics generated by the inverter. But there must be an LC filter applied, so that the transformer would not get overloaded.

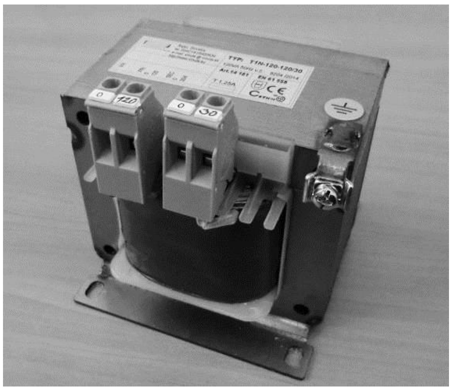

Fig. 2. Single-phase injection transformer - booster for DVR model

2.2. Transformer Tests

Various measurements and tests have been made on the real transformer in order to determine the exact parameters.

Transformer ratio

Transformer ratio is defined as a ration between primary and secondary voltage. The average value obtained by measurements is 3.64.

Winding resistance

The resistance of primary winding is 5 Ω and secondary 0.46 Ω (referred to the primary side is 6.1 Ω). The final resistance is 11.1 Ω.

Open-circuit test

Open-circuit test gives the values of a magnetizing current, a reactance, a no-load current and core losses. They are: I_{0N} = 154 mA, R_{FeN} = 5021 Ω, $X_{\mu N}$ = 1640 Ω, $L_{\mu N}$ = 5.22 H, P_{0N} = 11.5 W.

Short-circuit test

Short-circuit test is used to determine the winding impedances. U_{scN} = 11.35 V, z_{sc} = 4.7 %, P_{scN} = 11.25 W, X_{sc} = 2.37 Ω, $X_{\sigma 1}$ = 1.185 Ω, $X_{\sigma 2}$ = 0.09 Ω, $L_{\sigma 1}$ = 3.77 mH, $L_{\sigma 2}$ = 0.28 mH.

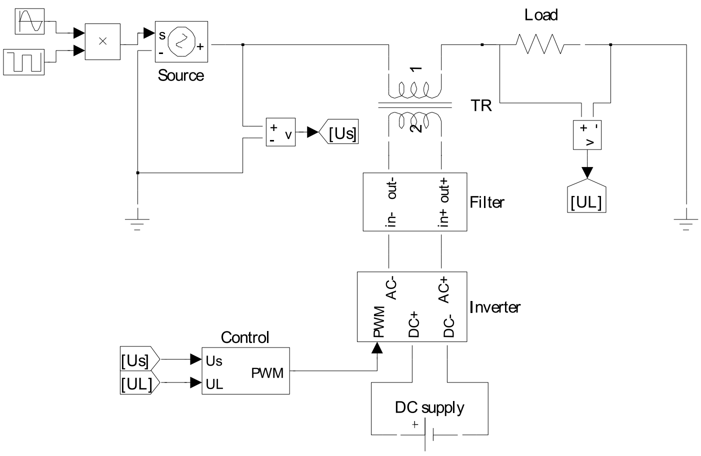

Fig. 3. Simulation model of DVR in Simulink

The parameters given by transformer tests are important mainly for implementation in simulation model. The simulation model was created in Matlab/Simulink (Fig. 3).

3. Verification and Results

The complete DVR model has been constructed in laboratory environment. The inverter is connected to the secondary terminals of the transformer. The PWM switching frequency is 5 kHz. The control algorithm is based on feed-forward method. The actual RMS value of source voltage is calculated and compared with rated value (127 V). DVR losses and voltage drop are also considered. The maximum injected voltage is 98 V and an in-phase control technique is implemented, which means, that compensating voltage is in phase with the line voltage at every moment. For the control unit 16-bit DSC microcontroller dsPIC33FJ128MC802 was used.

The correct function of DVR laboratory model can be seen in Fig. 4. There are 3 voltages – the source voltage in the upper picture, the injecting voltage in the middle and the load side voltage at the bottom. They were obtained from real model measurements. Several voltage sags occurred with different depths. At every moment, DVR dynamically computes and generates remaining voltage, which is transported to the line voltage using the injecting transformer. The load voltage is securely held within allowed limits.

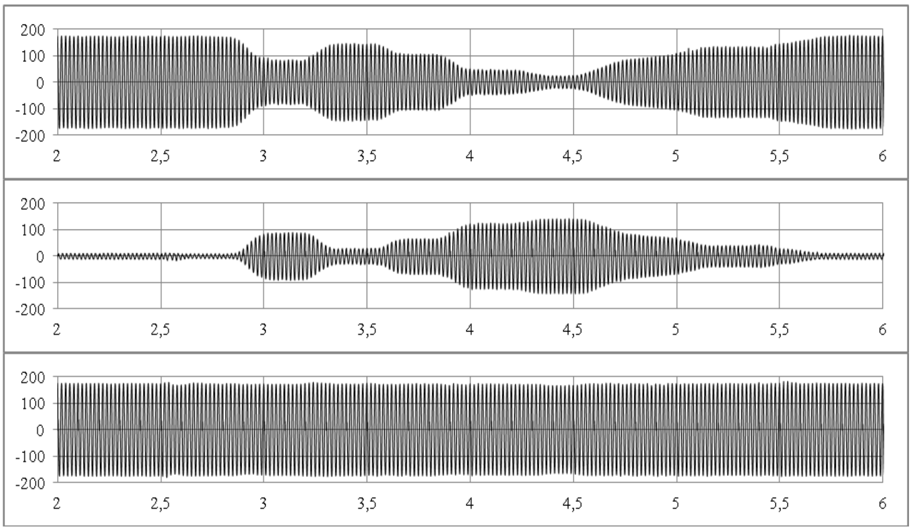

Fig. 4. DVR operation (measurement results)

Next, the simulation results are presented. Fig. 5 shows the source voltage, the injecting voltage and the load voltage during a short time period.

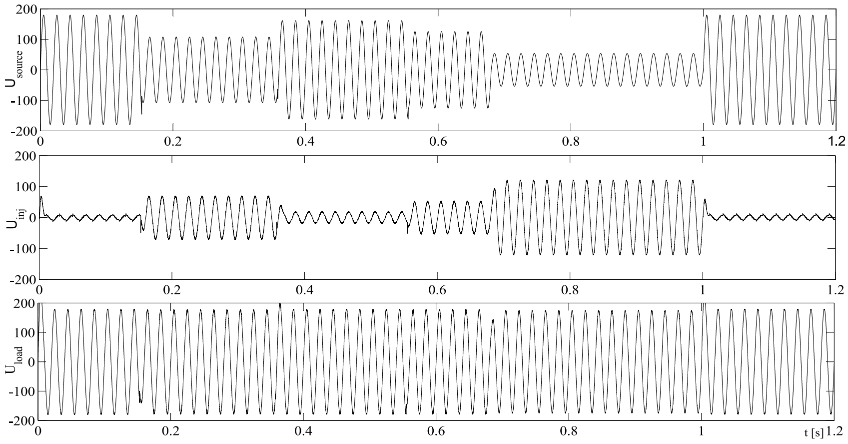

Fig. 5. DVR operation (simulation results)

As before, DVR works correctly and the compensating voltage is added to the source voltage through the injecting transformer. The load side voltage remains unaffected.

The voltage drop across the transformer in standby state and at rated load current is 24 V, which means that DVR should continuously compensate at least its own losses. Consequently, the VSC generates compensating voltage to cover voltage drop of DVR at every moment.

4. Conclusion

Verification tests as well as simulations proved that the injection transformer for DVR model is designed properly. It is able to inject a compensating voltage to the line voltage reliably and satisfactorily. In terms of rating, the transformer is two times overrated in order to subdue the saturation effect of the magnetic core. Core cross section area is doubled as well as rated power. For the injected voltage, there is a synchronization loop implemented in the control unit which ensures phase locking with the line voltage. Many various measurements and simulation tests have been performed. The phase shift of injected voltage waveform (due to the transformer impedance) is so small that it can be easily neglected.

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