Improvement of Electricity Distribution Services Using a DVR with a Constant DC Voltage Source Instaled in MV Connection Substations

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Abstract - **This paper analysis the Dynamic Voltage Restorer response provided for voltage sags mitigation in the electrical distribution networks with connection substation topology. Most often the voltage sags are caused by severe faults on the lines adjacent to main feeder and by faults on main feeder of connection substation. A realistic configuration of the electricity distribution network, similar to the distribution networks with connection substation that had been developed in Bucharest area is modeled. A DVR topology was chosen and implemented in Matlab/Simulink. The DVR performances are compared for different fault conditions. The results obtained during this study proves that the use of DVR for voltage sags mitigation on connection substation bus bars is a good solution for this type of distribution networks.**

Keywords— dynamic voltage restorer (DVR), electricity distribution networks, custom power devices, voltage sags.

I. INTRODUCTION

The power quality is defined by the quality of electric current and voltage, by involving the interaction between the system and electricity user into a closed system. The voltage and electric current quality refers to the deviation of voltage and current waves from its ideal sinusoidal shapes with constant amplitude and frequency. Obviously, if voltage leaves the proper quality domain, this phenomenon will negatively influence the electrical current quality, this claim being valid also for reverse state. The voltage quality concerns the system performance in terms of load need, while the electric current quality concerns the behavior of the loads supplied by the power system [1].

Nowadays, power electronic devices represent the most performing energy conversion technology that ensures both, flexibility and efficiency. In [2] power electronics is defined as technology that combines the effective use of electronic devices, application of electric circuits theory and their construction techniques and the development of analytical techniques for efficient electronic conversion, control and improvement of power system.

The main objective of this paper is to explore the performances of MV distribution system when a DVR is installed on connection substations bus bars. In order to analyze the improvement of electricity distribution services, a Matlab/Simulink application is developed and different fault conditions of MV system are simulated. A complex configuration of electricity distribution system is modeled. The DVRs' performance for different faults type and for different values of his voltage controller parameters is studied. Also, a solution to mitigate the voltage interruption during the automatic transfer switch operation has been proposed. The simulation results prove the correctness of the proposed solution.

DVR is a series Custom Power device that continuously monitors the delivered voltage and has the capability to inject or absorb the necessary voltage in order to maintain a constant voltage level at the end-user terminals. Custom Power devices are extensions of FACTS devices to electricity distribution networks, based on the availability of power electronics at a relatively reasonable price. When we discuss about Custom Power, in fact, we think to performance and reliability for electricity distribution networks and to an improved power quality with reasonable prices compared to the losses caused by an inadequate quality [3, 4].

II. TEST SYSTEM DESCRIPTION AND MODELING

To highlight the impact that the use of DVR has it on the quality of service in electricity distribution systems, this issue was analyzed for a complex looped structure of medium voltage (MV) network but with a radial operation. This type of configuration can be done either as a direct distribution network or as a secondary distribution network. In secondary distribution configurations, MV connection substations are implemented between the bus bars of the power substation and loads. Electrical lines built between power substation bus bars and connection substation are named feeders, and electrical lines that provide the power supply for the user, connected to MV bus bars of connection substation, for network topologies with connection substation, or those connected to medium voltage bus bar of power substation, for direct distribution topologies, are named distributor lines. In huge urban areas, these networks are built using underground electrical cables. Figure 1 shows the single-phase diagram of test electricity distribution system.

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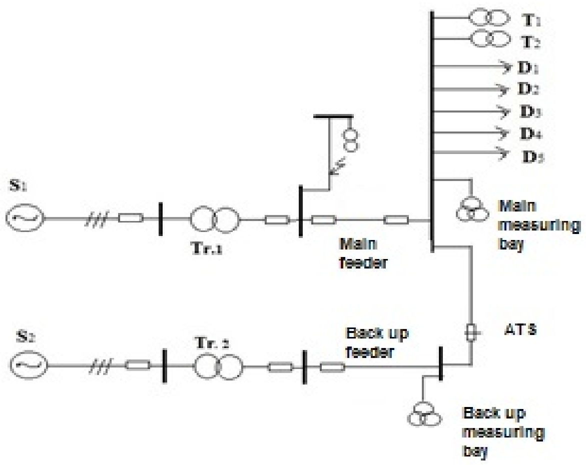

Figure 1. Single-phase diagram of electricity distribution test.

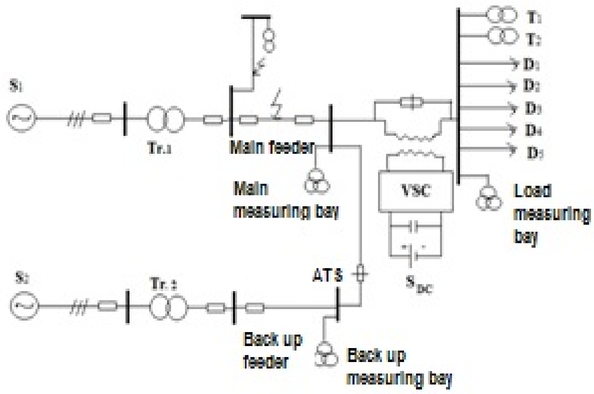

Figure 2. Connecting scheme to medium voltage bus bars of connection substation for DVR with a constant DC voltage source

This network uses a distribution configuration with connection substations. The main bus bar of connection substation supplies five branches through underground cables, branches realized with an input-output configuration of MV/LV substations, the second terminal of the line being connected to the main bus bar of this connection substation or to the main bus bar of another connection substation with the same voltage level. Having two supply sources, this electrical line is sectioned along the looped circuit according to a reducing losses strategy and providing a safe power supply for end-users. The connection substation is equipped with two medium voltage/low voltage transformers, in order to supply the low voltage loads from surrounding area of connection substation location and to provide the necessary supply for auxiliary services of connection substation, like operation monitoring facilities, remote control system, protection system and ventilation or heating system.

The two power injections from transmission system will be represented in the test system as voltage sources characterized by the short-circuit power and rated voltage. The two high voltage/medium voltage substations, that supply the connection substation, are represented by power transformers that supply the medium voltage bus bar of power substations.

In case of faults on adjacent MV lines fed from power substation bus bar that supplies the main feeder of connection substation, due to the failure of electrical equipment, users supplied through connection substation will suffer disturbances as voltage dips. In order to mitigate these voltage dips, the connection substation is equipped with a DVR connected to the main bus bar of connection substation. Next, the fact that this equipment manages to mitigate voltage dips caused by two-phase and three-phase faults voltage dips is analyzed, for a DVR topologies with constant auxiliary DC source. The single-phase diagram of test system including the DRV and his connection to medium voltage bus bars of connection substation is presented in figure 2.

Connection to electrical network is done through three single-phase power transformers (Tr dvr A, Tr drv B, Tr dvr C) and the DVR's voltage source inverter is represented as a power converter with a three level bridge structure. The three level bridge block has three arms, one for each phase of the network. Each arm consists of four insulate gate bipolar transistor, each transistor with an anti-parallel connected diode, and two diodes used to connect the bridge arms to the neutral point converters' DC link. The dc capacitor size was chosen according to the load power factor. In [5] it has been shown that higher power factor loads require higher dc capacitor size.

The test system response with DVR was studied by simulations realized in Matlab/Simulink. This simulation software allows us to implement the test system by representing each element of the electrical network using blocks already implemented in the simulation software library. The test system is implemented in Matlab/Simulink as in figure 3. This model allows us to study the system response for cases when faults occur in a line adjacent with main feeder. A two-phase fault occurs in an adjacent medium voltage line at time t = 0, 2 s and is removed by the protection systems of main VH/MV substation after 0.8 s.

III. CONTROL SYSTEM OF DVR

The control system, represented by voltage regulator, is presented in [6] and [7]. It is based on the transformation of the tree-phase instantaneous voltage frame into synchronous-rotating *dq* reference frame. The *dq*-components of the load voltage, obtained using Park's transformation, are compared with the reference voltages. In order to ensure a symmetric load voltage vector and an unitary power factor to the output terminals of controller, the *q* component of the reference voltage is chosen zero and the *d* component of the reference voltage is 1 (r.u.) . The obtained error represents the input signal for a proportional-integral controller and the signal obtained at the output terminals of PI controller are the *dq*-components of the voltage that must be injected by DVR.

The obtained voltage is transformed into the *abc* frame using reverse Park's transformation.

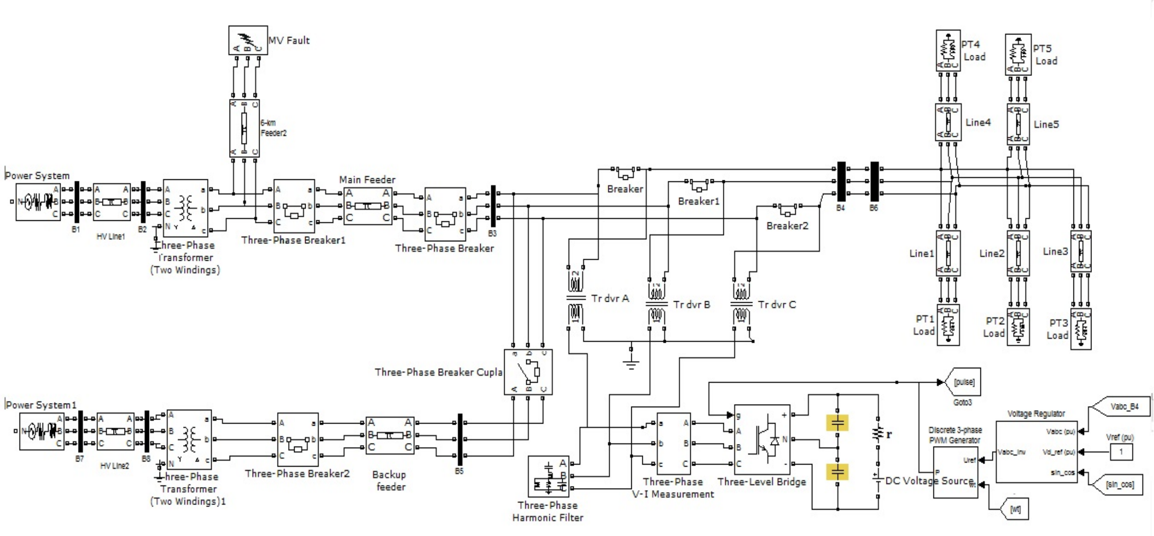

Figure 3. Matlab/Simulink implementation of test system, with DVR

The voltage injected by DVR is synchronized with the system voltage using a phase locked loop (PLL) module. The Park's transformation from *abc* components, obtained from the voltage measurement system, to *dq* components are also synchronized through the PLL module. The signal obtained from voltage controller is modulated using pulse width modulation (PWM) technique [6], [7]. A PWM generator offers the firing pulses for the inverter IGBTs.

IV. Voltage sags' mitigation using DVR with constant DC voltage source

The DRV response to voltage sag occurrence, for different values of K_P and K_I, it is analyzed. The study begins with the following values: K_P=0.4 and K_I=50. How DVR acts to restore the voltage level on the bus bar that supplies distributor lines is shown in figure 4.

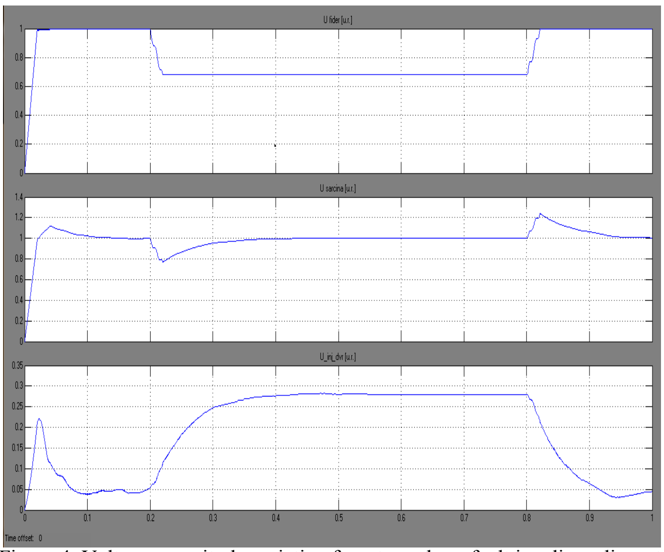

Figure 4. Voltage magnitude variation for a two-phase fault in a line adjacent to main feeder: a) voltage magnitude for main feeder; b) voltage amplitude on loads bus bar; c) the series voltage injected by DVR

The first diagram – seen from the top of figure 4 - shows the voltage magnitude on the main feeder of connection substation, in relative units. The second diagram presents the voltage magnitude on the loads bus bar of connection substation (also in relative units) and the third diagram represents the magnitude of voltage injected by DVR (in relative units).

Analyzing the diagrams from figure 4, it can be observed that DRV acts to restore the voltage level on loads bus bar to the rated value (1 r.u.). But the response is not fast enough, so end-users will experience the voltage amplitude variation, immediately after the occurrence of the fault in the adjacent line and also after fault removal after the protection system operation in the main power substation. The voltage level is restored to nominal value after approximately 7 periods.

From figure 5, which represent the voltage wave on the loads bus bar, for phase B, it can be seen that voltage distortion factor, during simulations, is 1,12 %, within the accepted level of THD, while, at the output terminals of voltage source inverter, the total harmonic distortion for the voltage injected to compensate the voltage dip is 36.44%.

For a three-phase fault, the disturbance magnitude is higher, facts that leads to an amplified effect for end-users, immediately after the occurrence of the fault in the adjacent line and after fault removal by protection systems. Also, the time period, necessary to restore the voltage level, after a disturbance occurrence, is higher, the voltage harmonic distortion grow up to 2,96 % and the average voltage magnitude during faults is different from rated value.

In order to improve the DVR performances, a harmonization process for the coefficients of PI controller is implemented. The new values for those two coefficients are: K_P=0.4 and K_I=500. Now, the DVR response is significantly improved, the equipment being able to maintain the voltage magnitude on the loads bus bar, inside the domain Un±10 %, for the entire disturbance manifestation period. Also, the response time was reduced and DVR was able to restore the voltage to the rated value in about 2 periods.

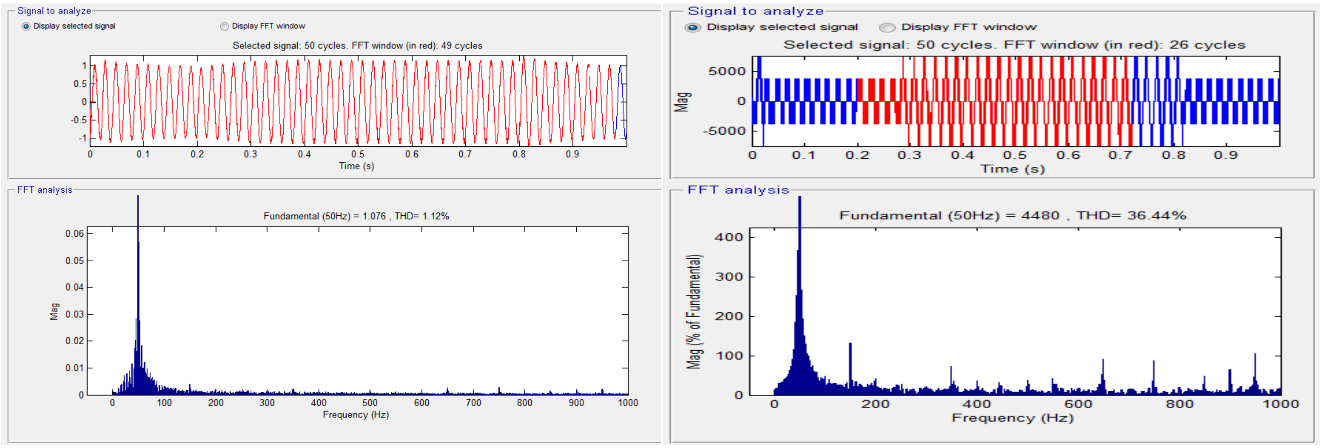

Figure 5. The voltage wave at the DVR output terminals, respectively, at the inverter output terminals

An improvement was achieved, but the harmonic distortion of the voltage wave increased to 3.16%.

Next, an improvement of the response time is obtained by increasing the value of K_I up to 5000. The DVR response is presented in figure 6 and it can be seen, that DVR is able to successfully compensate the voltage dips determined by a three-phase fault occurrence in a line adjacent to main feeder of connection substation, the voltage sag magnitude being 1.8 % of rated voltage value, compared with the case with K_I=500, when the voltage sag magnitude was 10 % of rated voltage value. The cost of this fast and efficient response is a non-significant increase of total harmonic distortion that, during voltage dip, reaches the value of 3.44%, lower than the 8 % value imposed by European EN 50160 norm [8].

Another situation encountered in the operation of medium voltage distribution networks built using a topology with connection substation is the fault occurrence in the main feeder of connection substation.

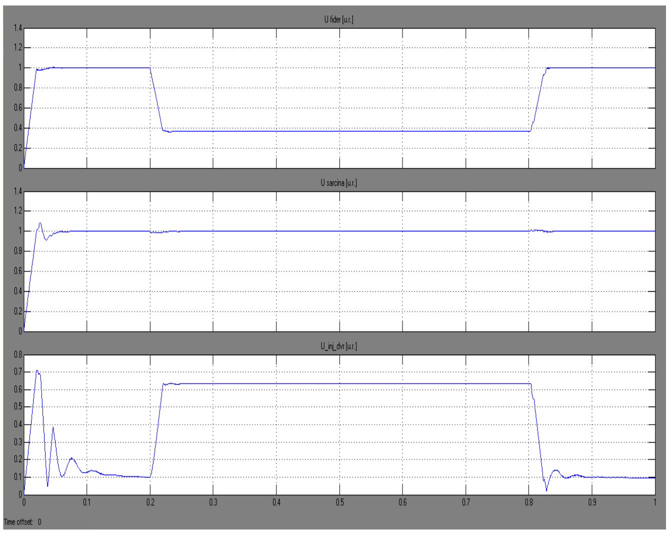

Figure 6. Voltage magnitude variation for a three-phase fault in a line adjacent to main feeder: a) voltage magnitude on main feeder; b) voltage amplitude on loads bus bar; c) the series voltage injected by DVR

For this case, after the fault removal by disconnecting the circuit-breaker of the main feeder, due to the operation of protective relay systems from upstream HV/MV substation, the supply restoration for loads fed from main bus bar of connection substation, is done after the operation of automatic transfer switch system, installed in connection substation. The timing chosen for this automation system is 3.5 seconds, correlated with response times of relay protection systems mounted upstream and downstream of the connection substation bus bars. For this scenario, the system response is not the desired one, because, after the opening of main feeder circuit-breaker mounted on the feeder bay in HV/MV power substation, all users supplied from main bus bar of connection substation are experiencing a temporary interruption of 2.6 seconds, until supply restoration moment, determined by automatic transfer switch operation.

In order to solve the temporarily interruption problem, it is necessary to use a directional over-current protection system mounted on the main feeder bay in connection substation, protection system that should sense the fault occurred upstream of connection substation bus bar. This protection system provides the opening command for circuit-breaker mounted on main feeder bay in the connection substation, after a time period equal with timing of the over-current protection system mounted on the main feeder bay in the upstream HV/MV power substation. In this case the automatic transfer switch operation will be accelerated, because the control logic of this automation system, involves the closing command activation for the backup supply immediately after the confirmation moment of the open position of the main feeder circuit breaker and the loads supplied from connection substation bus bar will be fed from the back up supply. It is considered that the operation time for circuit-breakers mounted in connection substation is small enough (1-2 periods).

The system response is presented in figure 7, where it can be seen that the voltage on the connection substation bus bars suffers only a small perturbation during the time between the main feeder circuit-breaker opening moment and the backup circuit-breaker closing moment.

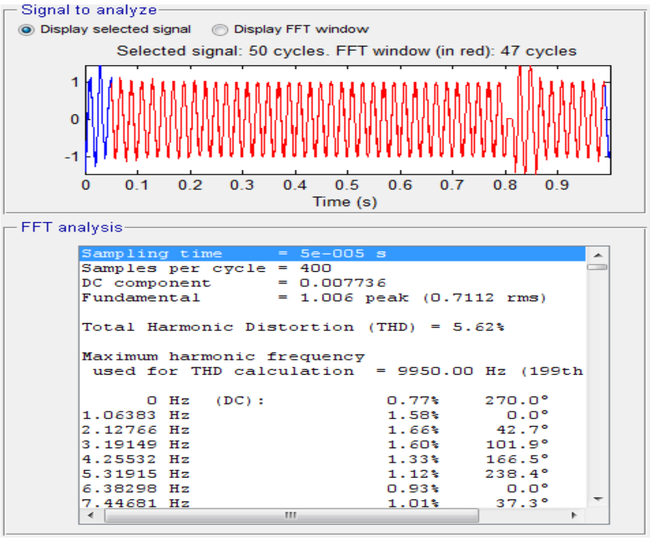

Figure 7. The voltage wave analysis, for the loads bus bar of connection substation, for three-phase fault on main feeder occurrence, with a directional over-current protection mounted on main feeder bay in connection substation, for K_P=0,4 , K_I=5000

During the studied time period, the switching of these circuit-breakers is increasing the harmonic distortion to the value of 5.62 %

CONCLUSIONS

The study for the analysis of the DVR response, provided for voltage sags mitigation in the electrical distribution networks with connection substation topology, was realized for a realistic configuration of the electricity distribution network, similar to the distribution networks with connection substation which were being developed in Bucharest area. Voltage sags caused by severe faults on the lines adjacent to main feeder or by faults on the main feeder of connection substation had been simulated. The DVRs' performances for different faults type were highlighted and the DVRs' response for different values of his voltage controller parameters was analyzed.

A solution to mitigate the voltage interruption during the operation of automatic transfer switch installed in the medium voltage connection substation has been proposed.

The obtained results prove the ability of DVR to restore the voltage level at the terminals of end-users supplied through connection substation, for the DVR topology in which the energy of DC link integrated into DVRs' structure is provided by a continuous DC source. For this topology, a renewable energy source based on photovoltaic cells technology may be used together with a battery storage system (BSS), in order to provide a constant voltage level during voltage disturbances.

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