DYNAMIC RESPONSE OF DISTRIBUTED SYNCHRONOUS GENERATORS ON FAULTS IN HV AND MV NETWORKS

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ABSTRACT
Connection of distributed generators (DG) on existing power distribution networks requires solution of technical, economical and regulatory issues. A brief description of current status of DG in Bosnia and Herzegovina, with special attention to the technical impact of integration of small hydro power plants with synchronous generators, is given in this paper. Dynamic response of DG (namely small hydro power plants with synchronous generators) on disturbances in HV and MV networks is analyzed in detail. Simulations of DG dynamic response are performed using free, open-source MATLAB/PSAT software package on a simple test model of distribution network with DG. Several scenarios are studied. Finally, areas for further research are identified and presented.

INTRODUCTION
During recent years, integration of distributed generation (DG) in existing power systems has taken place with great extent. This development is driven by the increasing liberalization of the electricity market, growing concern over greenhouse gases emissions and improvement in DG technologies. Generally, connection of DG on distribution network (DN) requires solution of technical, economic and regulatory issues. In parallel with the development of specific market mechanisms and defining the status of DG there is increased interest in evaluating the technical effects of DG on power system operation.

Bosnia and Herzegovina (B&H) has started process of liberalization of the electricity market that also includes DG related issues. Currently initial, mainly private, investments in DG, primarily in small hydro power plants, have been started. DG are usually equipped with synchronous generators and some are connected to “electrically weak DN” usually with low local consumption. Basic regulations about connection criteria for DG are already set, but analyses of technical impact of DG, which require detailed simulation based analyses, are not performed regularly. The participation of DG in emergency state control becomes very interesting topic with connection of significant DG capacities as it is expected. This requires analyses of dynamic response of DG on disturbances/faults in HV and MV networks. Possibility of using MATLAB/PSAT software for analyses of DG response in dynamic state is illustrated in this paper on a simple test power system.

TECHNICAL ASPECTS OF INTEGRATION OF DG
Due to the locally available resources of small scale, DG units are mostly connected at the distribution level. Main technical issues that should be analyzed are: impact on network voltage changes and power flows, increase in network fault levels, impact on power quality, integration in current protection system and impact on system stability [1]. Technical recommendations for DG connection limit negative impacts of DG on power system but they are not unified in different countries. Many researches have been studying the impact of DG in steady state. Dynamic response and possibility for ancillary services in emergency situations from DG present a new area of research of power systems with DG.

Current activity frame for DG in Bosnia and Herzegovina
In B&H connection of DG on power DN is defined by technical recommendations of electric power utilities that operate DN. Technical recommendation for the connection and operation of DG in Electric Power Company of B&H (EPBiH) provide the basic connection criteria for DG, requirements for production and control of reactive power, depending on the DG capacity, and requirements on measurement and protection systems. Due to negative impact of some of DG that were connected to weak DN current rules, defined by the public utilities (i.e. EPBiH) for the connection and operation of DG, are very restrictive. Restrictive policies regarding the impossibility of islanding of DG and lack of possibility for provision of DN “support” from DG are result of several factors: non-existence of adequate regulatory framework, non-systematic approach in decision-normative documents and lack of appropriate parameters to evaluate the possible contribution of DG.

ANALYSES OF DN TEST MODEL WITH DG USING MATLAB-PSAT OPEN SOURCE PROGRAM
Evaluation of MATLAB/PSAT software for system analyses of DN with DG is presented in this section.

PSAT as a simulation tool
PSAT (Power System Analysis Toolbox) is an open code free MATLAB based toolbox for electric power system
analyses and control [2]. The main features of PSAT are: Power Flow; Continuation and Optimal Power Flow; Small Signal Stability Analysis; Time Domain Simulation; PMU etc. PSAT core is the power flow routine. Once the power flow has been solved, which is followed by the state variable initialization, further static and/or dynamic analysis can be activated. Transient stability analysis of DN with DG is evaluated in further sections using PSAT Time Domain Simulation feature.

**Stability analysis of single machine test model with DG**

Simple single machine test model with DG, as shown in Figure 1, is used for analysis. Illustration of PSAT performed simulation results is derived based on the equal area criterion [3].

![Figure 1. PSAT model for stability analysis of single machine test model](image)

The aim of the analysis was to analyze the impact of resistance R of connecting line on transient response of DG. It is assumed that the increased ratio R/X, as the specific feature of the DN compared to HV transmission networks, will have double effect:

1. It will contribute to improving transient response of DG since it will absorb certain amount of kinetic energy (due to R^2 losses) during fault duration.
2. After fault clearing, R has a double impact: a) Due to R^2 losses, R helps in easier absorbing of accumulated kinetic energy thus maintaining transient stability. b) R reduces the transfer capacity of the network and synchronizing power between DG and the network, which negatively affects the transient stability.

During fault period, certain amount of energy which can not be transmitted into the network is transformed in kinetic energy according to the swing equation:

\[ \frac{2H}{\omega_0} \frac{d\delta}{dt} = P_m - P_e = P_a. \]

When rotor angle \( \delta_0 \) achieves new value \( \delta_1 \), surface area on power angle curve when balance is reached refers to the value of \( A_1 \). But, rotor speed is higher than synchronous and both rotor angle and electric force further increase. After fault clearance, sufficient transfer capacity of the network is needed for the absorption of accumulated kinetic energy, actually sufficient synchronizing forces are needed. Period when \( \omega > \omega_0 \), but \( \omega(t) \) is decreasing, is critical for keeping system in synchronism. This period presents the area \( A_2 \) in the equal area criterion. If synchronous operation of machine is threatened, when \( \omega(t) \) is decreasing and \( \delta(t) \) is increasing, actually if \( A_2 < A_1 \), system instability occurs.

Fault with duration of 0.1 s on HV bus is analyzed. Line resistance R was neglected in one case (\( X \gg R \)), and in the second case it was included (\( X \approx R \)). Less increase in angle during fault when \( X \approx R \), as shown in Figure 2., is a consequence of the of the fact that certain amount of kinetic energy is absorbed as power losses in DN. Power angle curves are analyzed for different cases. Resistance R decreases the value of surface area \( A_1 \) so transient stability is improved as shown in Figure 3. After fault clearance, R contributes in easier absorbing of accumulated kinetic energy that improves transient stability, too. However, R contributes in reducing of network transfer capacity, actually in reducing synchronizing power between DG and network, thus having a negative impact on transient stability as well.

![Figure 2. Impact of line resistance R on angle of DG](image)

![Figure 3. Power angle curve for DG connected to infinite bus via line with X \( \approx \) R](image)

**PSAT analyses of dynamic response of DG on network test model**

Test model of DN used for analyses (with some modifications) is defined in order to present real DN with DG and to be suitable for evaluation. Existing element models from PSAT/Simulink library are used as shown in...
Figure 4. Voltage levels in test model are: 110, 10 and 0.4 kV. Consumers and four DG are connected to MV lines for analyses of different cases (e.g. typical arrangement connection of DG in B&H). Four DG are equipped with synchronous generators and adequate regulating units and are connected via 10/0.4 kV transformers. Dynamics of synchronous DG is described with 4th order equation model in PSAT/Simulink.

Several different scenarios of faults and disturbances are evaluated [4] and some results of performed simulations are presented below.

Scenario 1
Dynamic response of DG on three phase short circuit on the bus 110 kV with duration of 0.1 s is analyzed. DG remain stable and normal operation of DG has to be enabled with adequate protection settings.

Scenario 2
Dynamic response of DG on the three phase faults in HV network with duration of 0.1 s, with both successful and unsuccessful automatic reclosing of HV transmission line after 0.1 s, is analyzed. Automatic reclosing should not lead to disconnection of DG if its stability is not threatened. Before line reclosing, a part of DN with DG remains in so-called islanded operation. Transient response of DG during this period also depends on the balance of generation and consumption in the islanded part of the network.

Scenario 3
Dynamic response of DG on the three phase faults in HV network with duration of 0.1 s, with both successful and unsuccessful automatic reclosing of HV transmission line after 0.1 s, is analyzed. Automatic reclosing should not lead to disconnection of DG if its stability is not threatened. Before line reclosing, a part of DN with DG remains in so-called islanded operation. Transient response of DG during this period also depends on the balance of generation and consumption in the islanded part of the network.
Dynamic response of DG on loss of 100 MW generation in t=0.5 s is analyzed (active power unbalance of app. 14%). There is no significant impact on DG during disturbance but better response of DG is obtained by increasing of DG inertia as shown on Figure 11.

Figure 8. Angular velocity of DG3 for unsuccessful reclosing of HV line with different power balance

Figure 9. Angle of DG4 for unsuccessful reclosing of HV line with different inertia of DG

Scenario 4
Comparison of DG responses for radial and meshed test model network with DG is analyzed. Oscillations are much smaller or transient response of DG is more stable when network has a meshed structure as shown in Figure 10.

Figure 10. Angular velocity of DG3 for fault in HV network and radial or meshed DN structure

Scenario 5
Analysis of dynamic response of DG on system disturbance with significant power unbalance (i.e. loss of great generation capacity) is performed where dynamic response of speed regulating units plays an important role. Large consumer with active load of 800 MW and a generator with capacity of 100 MW are connected on the same 110 kV bus.

CONCLUSION
This paper gives a certain contribution to overall analyses that should be performed in order to clearly specify the status of DG in B&H. On a simple test system evaluation of free open source MATLAB/PSAT software is demonstrated. Existing models in PSAT, with respect to certain restrictions, enable satisfactory analyses of dynamic response on system disturbances and provide base for identification of response characteristics. It is shown that transient stability is not an issue for synchronous DG despite low inertia, limited voltage and power regulation, radial structure etc. because of the positive impact of line resistance R. As shown, dynamic response of DG can be improved by increasing DG inertia (i.e. by adding flywheels). Further research [5] is recommended in the following areas: a) coordination of protection and application of modern power system protection, b) anti-islanding methods and techniques.

REFERENCES