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Dynamic equivalents for calculation of power system restoration

The power system must be prepared for the situation that all or a major portion of the system is forced out of service. This can exist as result of a particularly severe faults resulting in the loss of stability and the need for many generators to shut down.

In 2003 some European power systems (Italy, parts of London and Scandinavia) but also North America has suffered widespread outages. In the United States over the past 15 years, the large-scale blackouts there have been more frequent than can be explained by random damage.

If the blackout occurs, the system as quickly as possible must be restored to normal operations. In the event of a total blackout the power system is divided into different subsystems so that in the event of total grid failure, initially each subsystem is to be restored independently. The initial seconds of the restoration are extremely precious and the required operation made at first moment can help in exactly restoration of the system but any error or small delay during the initial action may cause ending in a sudden, catastrophic change.

Between many standards which are used for the preparing of the scenario of system restoration is the requirement that the system operator must, at least once a year simulate system restoration using information on blackstart generation, transmission, nonblackstart generation, load, and the restoration plan [1]. The adequate security coordinator will certify the restoration plan only if the results of simulation prove a high probability that restoration will be successful. As a consequence each restoration plan must ensure that the guidelines and procedures for restoration are carried out by trained operating staff with good enough experiences. This requires a restoration simulation program with the suitable power system representation.

The simulation must take into consideration whole spectrums of phenomena which occur from the fault begin till the restoration of power system. The dynamic behavior of connected and cooperated power systems need detailed investigation that will recognize their performance during emergency situation within the whole network. For instance the incorrect operation of protection devices (which are designed to isolate the faulted portion without causing a loss of load to the remaining power system) can cause bad consequences included cascaded disconnection of system components and finally blackout. For this purpose the simulation of electromagnetic and electromechanical transient during faults are required for the prediction and recognition of any incorrect operation of automatic protection systems.

During the restoration process depending on scenario practically both the electromechanical and electromagnetic transients will occur. In the worst case, if the system has a complete shut down, the open breakers need to be re-closed to connect the loads and the sequence of breaker operations may affect the voltages and the currents. In such situation also the multiple switching operations are possible and the transients expected from the switching action have to be analyzed. It must be taken into account that a restoration sequence staring from two subsystems will require closing a breaker with different voltage levels on the two sides of the breaker, what will result in significant transients.

Till now there is not at disposal the universal power system representation which can be used for the simulation of transients during whole restoration process. The representation of the individual network elements and also the subsystem must correspond to the specific frequency range of the particular transient phenomena. A single physical component may have different model representations depending upon the context of the problems. Power system networks, as shown in Figure 1, are subjected to many forms of transient phenomena ranging from the relatively slow electromechanical oscillation associated with synchronous machine instability through electromagnetic transients to the fast variation in voltage and current.

The need for the fast but also correct analysis of power systems restoration extorts the reduction of subsystems that are outside the focus of investigation. Replacing subsystems that comprise hundreds or thousands of active components with suitable dynamic equivalents will be essential for power system dynamic analysis. The network equivalent model development originates from the need to have readily available detailed only those component they are of primary interest. This arises not only due to the computational time saving but also from the difficulties of modeling and determining of parameters of a large number of components within the subsystem area. However, it is beyond any doubt that the reduction of the network leads to some inaccuracies of the obtained computed results. Therefore in the previous
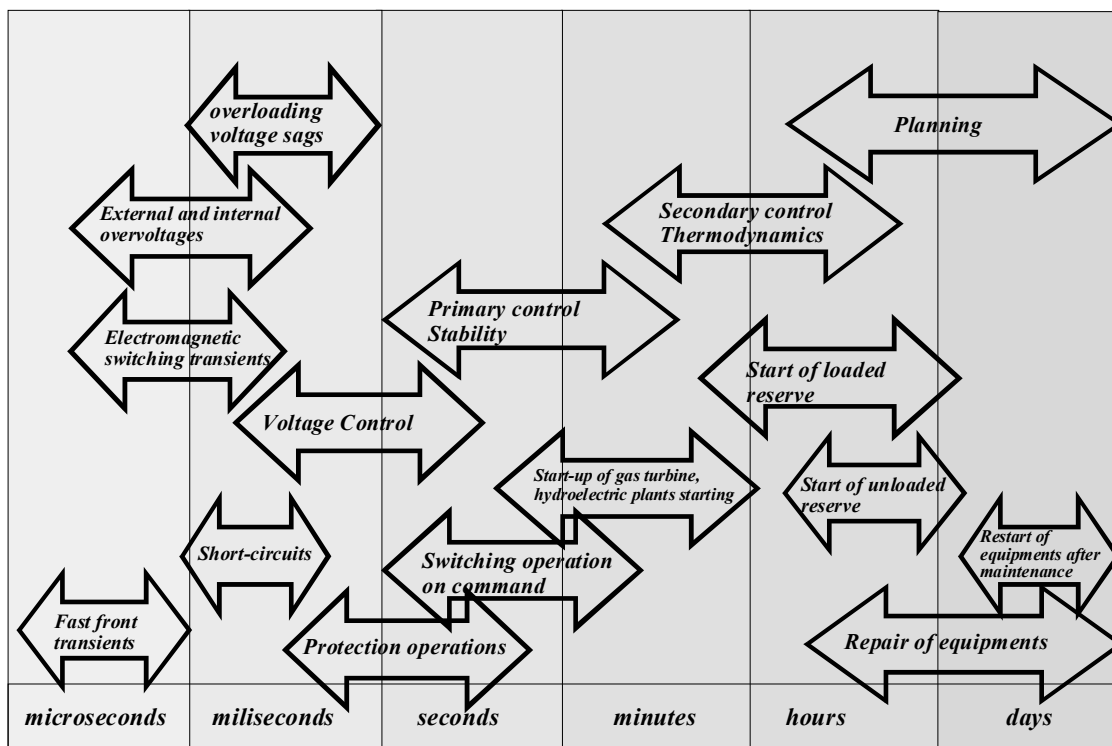
Figure 1 Phenomena in power system

analysis connecting with the identification of structure and parameters of equivalent systems was very important to find a compromise between the accurate and reduced network representation for each transient fault analysis, according to the analyzed case and the foreseen utilization of the results. The new possibility - Artificial Neural Networks (ANN) as alternative technique for developing dynamic equivalents using for the power system restoration is presented in this paper.

Creating of dynamic equivalents

During the power system blackout occurs the dividing of the power system into small islanding systems as shown in Figure 2.
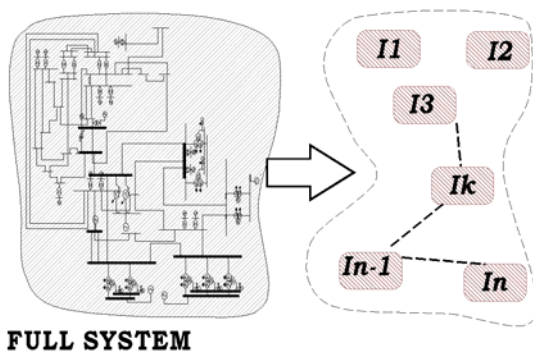

Fig. 2 Network reduction

For the simulation of power system restoration it is not important the representation in detail of each components of the islanding system. The network is investigated regarding to start up and operation of island networks. Therefore the most important is to find a simplified and verified equivalent network for each island systems. For such investigations the basic information about electromechanical transients are required. In the past the searching of the equivalent network for the electromechanical transient investigations (transient stability analysis), was mostly made by the reduction of the original system. The three basic approaches are used by the reduction of the original system to its dynamic equivalent (Fig. 3):

- modal analysis,
- coherency based methods,
- modal-coherency technique.

In modal technique the equivalent system is determined after reduction of complex nonlinear representation of external system to linear digitalized of state equation model [3, 4]. An alternative approach is based on the concept of coherency, where the coherent group of machines is obtained and aggregated to a single equivalent machine for each group [5, 6, 7]. Nonlinear approaches for creating dynamic equivalents are usually based on the coherency concept, where coherent groups of synchronous generators are identified and aggregated to a single equivalent machine for each group. The review of papers shows different opinion about these two methods. Some authors present the results of investigations receiving with the help of modal analysis, but in many others is preferred the network reduction based on the coherency, sometimes with the expression that the reduced models obtained by modal analysis cannot be used without modifications to stability programs. Both methods as well as

combinations of both are used in some computer programs. The coherency-based approach was implemented to DYN-RED package [8], and the results for large-scale system testing, and for the constructing of dynamic equivalents, shown that the basic procedure employed by DYNRED should yield reasonably accurate equivalent representations. The combination of the slow-coherency and multi-area selective modal analysis was implemented into the EUROSTAG [9] simulation package.

New idea of solution of equivalent systems

The analysis of electromechanical transient during fault conditions can be solved only under condition that results are given from:
1. measurements,
2. calculations made in complex system without any simplification with detailed representation of each element of system,
3. calculations made in equivalent network.

First condition is mostly not possible for realization because of technical, economical and security reasons. A second condition is also mostly not possible, because of the problem to get the data of each element of big power system. Third condition is possible after verifications of results received in equivalent network with the help of comparison with measured or calculated results in primary (not reduced) system. The above presented (p. 2) methods for the search of structure and identification of parameter of equivalent system require many restrictions. By using modal analysis technique the time-consuming computation of eigenvalues is required and the resulting reduced differential equations system is not representing without modification for the stability calculations.

The new idea introduced [10] for the optimizing of equivalent network using ANN, is proposed also in this paper for the calculation of electromechanical transient during restoration of power system.

The idea behind the proposed technique is to replace all active components in a complex external system by a dynamic ANN, which is connected to the same boundary buses however the lumped equivalent loads are connected at the boundary nodes to account for the passive elements in the external area. The principles of the proposed dynamic equivalency approach are explained in Fig. 3 for one boundary bus.
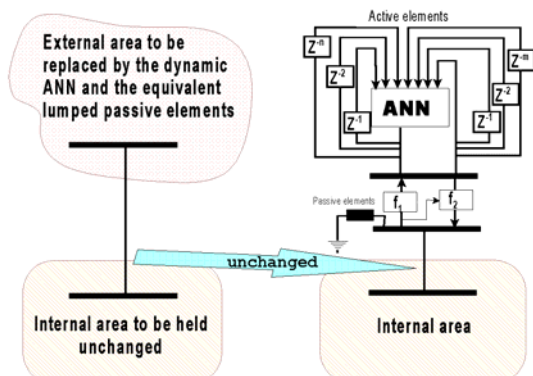

Fig. 3 Principles of dynamic equivalencing approach

At each time interval, the instantaneous values of boundary-bus voltages are used to compute the normalized voltage-deviations through the function (f1). The normalized voltage deviations are introduced to the equivalent model and processed with previous normalized current and voltage deviations to calculate the present normalized current deviations at each boundary bus using ANN. The normalized deviations of currents and voltages are computed based on their initial conditions [10]. Currents (real and imaginary parts) are chosen as outputs from ANN as they are found to give better convergence in the training process compared with the alternative active and reactive power.

The actual values of complex currents are calculated inside the function (f2) and if the used simulation software works with injected powers, they can be calculated outside the ANN as shown in Fig. 3. Nowadays the simulating of equivalent model is a very fast and simple task even if the structure of the ANN comprises many parameters. The utilization of past values of currents and voltages as inputs to the ANN is essential to obtain a dynamic equivalent, whose order depends on the number of recurrent loops.

Description of the test network and result examples

A 16-machine 380/220-kV-network [11] is used in this research to test and verify the proposed technique. In this network the synchronous generators, connected via transformers to the high voltage nodes are represented by fifth-order models. This area is assumed as the external network, which should be replaced by an equivalent dynamic model and the high voltage system is modelled and simulated in detail.

In this network the simulations were made for the 3-phase fault, in chosen localization (marked in Figure 4). Two nodes were marked for the comparison of results of calculation in original system and after reduction = node no. 5 and no. 14.

The calculations were later repeated for the reduced network; however the reduction was made for the area marked in Figure 4. The modelling and simulation are accomplished using the simulation package "Power System Dynamics (PSD)" [12]. Complex voltages, power transfer and injected currents all at the boundary-buses are stored during the fault simulation. Subsequently, these results have been used to prepare suitable patterns for ANN training.

After training the ANN in the offline mode, it is tested under the same disturbances used in the training process, however, in the online mode with re-coupled outputs in nodes no. 1 and 2, and presented as example in Figures 6 and 7 respectively.

The current values – real and imaginary part calculated in original – primary system and received in system with equivalent subsystem are compared for the 3-phase faults simulated

It is clear that very good results – almost the same - values received in primary and reduced system, shown the rightness of assumed methods of calculations and optimization.
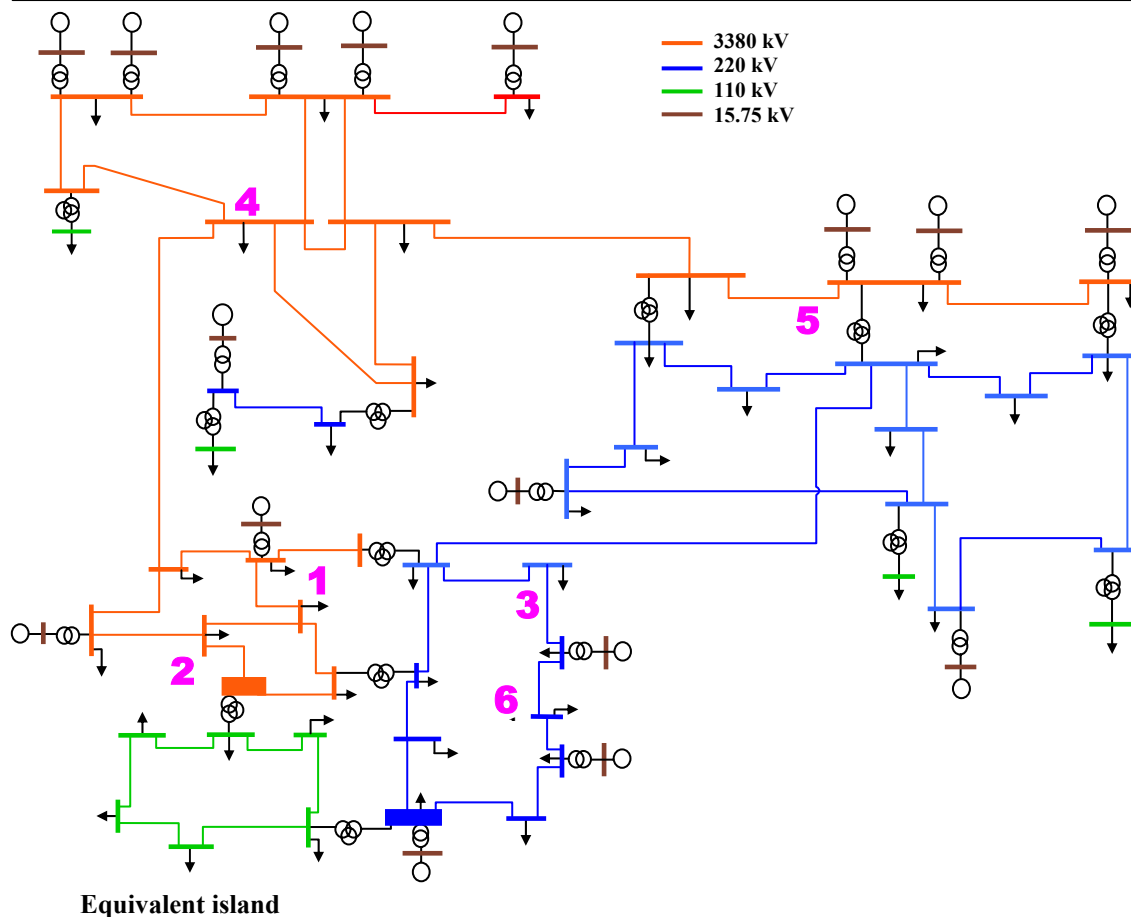
3380 kV
220 kV
110 kV
15.75 kV

Equivalent island

Fig. 4. Single line diagram of tested PST16 network internal system

I_1 (Real part)

I_2 (Real part)
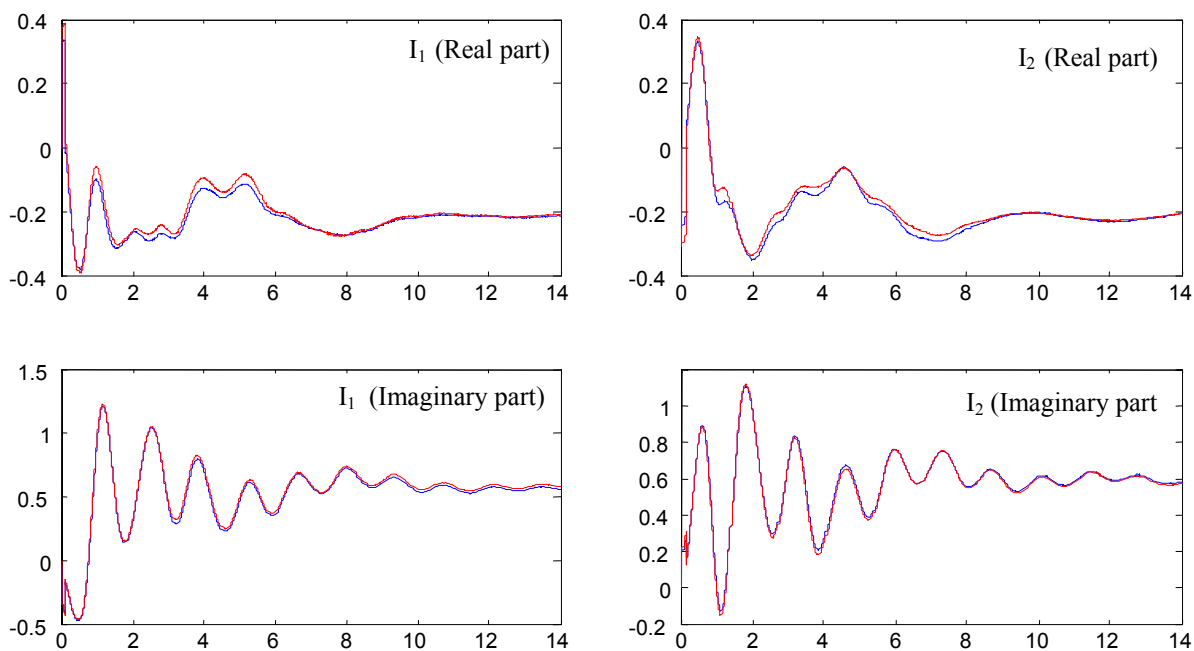
I_1 (Imaginary part)

I_2 (Imaginary part

Fig. 6 Comparison of current values calculated in original and
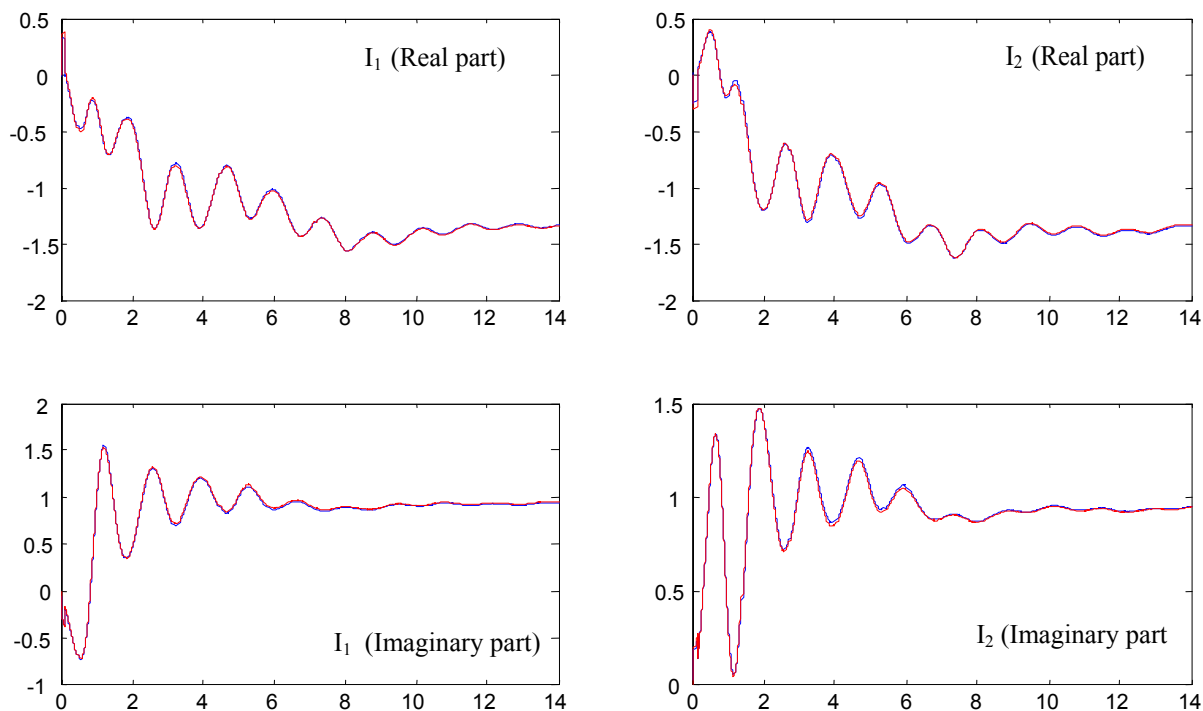reduced network for the case of fault in node 1

Fig. 7 Comparison of current values calculated in original and
reduced network for the case of fault in node 2

Conclusions

A new approach introduced for the identification of dynamic equivalents to distribution systems was proposed in this paper also for the use of the restoration calculations. The method based on dynamic ANNs is universal and also applicable also when changing the contribution of active distribution units in covering the local demand. In addition by use of the ANN-based equivalent only variables at the boundary buses are needed for the training process. However, it can be trained also with time series recorded in real systems. All simulation results show a very good agreement between the detailed and the ANN-based equivalent model general, the results encourage the use of ANN-based dynamic equivalents especially for restoration calculation when the power system island can be replaced by equivalent network.

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