Identification of Dynamic Equivalents for Distribution Power Networks using Recurrent ANNs

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***Abstract*— This paper introduces a recurrent ANN-based dynamic equivalent for distribution networks in interconnected power systems and outlines the implementation of such equivalents in simulation packages. According to this approach, a recurrent ANN is trained in the offline mode using measurements only at boundary buses and hence it is independent of the network size and complexity. Then, a suitable dynamic model, which depends on the structure and parameters of the ANN, is developed and implemented within the simulation program. As the proposed ANN-based dynamic equivalent interacts with the retained subsystem in the online mode, it can be used for different stability analysis purposes. The proposed strategy is applied to define a dynamic equivalent for a distribution system containing a large number of active sources in a multi-machine network. The dynamic performances of the original full network and that containing the equivalent model are simulated and their behaviours are compared under different disturbances in the retained network. The practical capability of the ANN in developing simple but accurate dynamic equivalents for distribution power networks is demonstrated through these comparisons.**

***Index Term*—** Distributed generation, Dynamic equivalents, Network reduction, Neural networks, Power system analysis

I. INTRODUCTION

THE COMPUTATIONAL difficulty in handling stability problems of large interconnected power systems increases dramatically with the rapid increase of the size of networks [1]. It is expected that a considerable number of active sources, i.e. Distributed Generation "DG" with significant installed capacity will be connected to the existing distribution systems in the near future [2]. Hence, modelling the large number of active sources in detail will be a formidable task [3, 4]. On the other hand, approximating the dynamics of these networks using passive lumped loads will lack the sufficient accuracy necessary to simulate the dynamic behaviour of these subsystems. In studies, which focus only on the high-voltage areas in large interconnected networks, it will be adequate to derive simple equivalents for the distribution networks, which are outside the main focus of this investigation [3]. However, any realistic dynamic model has to give reasonable approximations to the dynamics of active sources and their impacts on the high-voltage networks.

The classical nonlinear equivalency depends on the coherency concept, where a group of coherent generators is aggregated into a single equivalent one [5-7]. The single generator is then used to constitute the reduced-order dynamic equivalent for the coherent group. This approach has the advantage of describing the equivalent generators by similar nonlinear models as the replaced machines and hence they are compatible with other components in the network. To define the coherent groups and to perform the aggregation process, a complete knowledge of the behaviour of the replaced generators is required. In some cases, the available measurements may be insufficient to develop accurate and reliable equivalents [8]. This is true especially with the development of equivalent regulators, such as suitable AVR and governors, for the equivalent generators [9, 10].

With the spread of active sources with effective dynamic impact, i.e. DG units, some difficulties regarding classical equivalence approaches will arise. The coherency-equivalent techniques, which depend on analyzing the electromechanical behaviour of generators through angular speeds or rotor angles, will not be suitable for many DG units, which are linked to the network through inverter interfaces. In additions, several prominent DG units, like fuel cells and photovoltaic, are not characterised by angles or speeds. Therefore, new general equivalence approaches have to be developed to take into account the nature of the new types of sources.

In this paper, a generic nonlinear dynamic equivalent model based on recurrent ANN is presented and used to replace a distribution system containing a large number of active DG units. The development of such dynamic equivalent does not obligate specifying a particular model configuration in advance. Rather, the structure and parameter description of the ANN (activation functions, biases and weights) will define the construction of the dynamic model. The main advantage of this equivalent is the need for measurements only at boundary buses between reduced and retained systems. Also, the accuracy of the developed model is not significantly affected by changing the operating point and hence it is not restricted to certain initial power-flow conditions. Once well-trained and tested, the ANN-based equivalent can be used in simulation, analysis and control-design procedures.

The effectiveness and validity of the proposed approach is demonstrated by replacing a 110-kV network and the underlying low-voltage area by an ANN-based equivalent. In the low voltage area, a total number of 112 active DG units including fuel cells and micro-turbines are modelled. A number of disturbances are simulated in the retained network, where voltage and current waveforms are used to extract suitable patterns to train and test the ANN. The ANN-based dynamic equivalent is then implemented to replace the distribution system for online interaction with the retained network. Simulation results prove high accuracy of the alternative ANN-based equivalent, which encourage the implementation of the proposed approach in large interconnected power systems.

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II. ANN-Based Dynamic Equivalent

ANNs have high capability to deal with complicated nonlinear problems and to resemble the behaviour of the original systems in a general frame [8, 11]. A good-trained ANN can be used to simulate the dynamics of complex distribution systems and interact with other parts of the network without considerable divergence from the actual behaviour. Therefore, it is suggested to substitute all active components in the distribution system by a recurrent ANN. The recurrent structure of the ANN is required to capture the dynamic behaviour of the replaced network and to enable the online interaction with the retained network. In addition, passive loads can be represented as lumped equivalent elements at the boundary nodes using the conventional practice. In the current investigated case, constant-impedance equivalent elements are used to represent the passive loads. Voltage and frequency dependency of the loads can also be modelled using the general exponential relations.

The separation between active and passive elements extends the validity of the equivalent to cover situations where generating and loading conditions change inside the replaced system itself. In this case, changes of loading conditions in the distribution network are simulated by adjusting the equivalent lumped elements at boundary buses. On the other hand, slight modifications on the initial conditions of currents and voltages can account for varying the generation status of DG units. The entire distribution system can also be replaced by the recurrent ANN if there is difficulty in representing the passive loads separately. However, the separation between active and passive elements gives more flexibility in the analysis.

In addition to the ANN itself, the dynamic equivalent requires two supplementary functions: a mapping function to prepare the ANN inputs and demapping function to process the outputs from the ANN and to calculate complex power. These two functions represent the interface between the ANN and the external network. The equivalent model will interact with the retained system through the boundary buses between the two original subsystems. It will be perturbed by the voltages at the boundary buses and reacts by supplying the corresponding complex power at each time interval. The ANN itself will act as a Norton model, where the normalized deviations of voltages according to the steady state values are used as main inputs and the normalized deviations of currents represent the outputs. In addition to the input voltages, past values of currents and voltages are also introduced at the input layer to achieve the recurrent structure. With this construction, the ANN will be able to capture the dynamic nature of the original network and to maintain the continuous-time operation of the entire network.

The current rather than power is used as output from the ANN as it represents independent variable, whereas power depends on the voltage, which is an input to the ANN. Therefore the use of current gives better convergence in the training process compared to the complex power due to the complete decoupling between outputs and inputs of the ANN. The use of normalized deviations as inputs and outputs in the ANN allows the use of the equivalent model under new initial power-flow condition. The ANN in this case represents a normalized model scaled on initial conditions at the boundary buses. Augmenting this feature with the independent representation of active and passive elements results in a universal model, which is capable of simulating the original system under different operating conditions.

The basic principles behind the proposed approach are explained in Fig. 1. As shown in the figure, the dynamic equivalent can recognise the operation state of the retained network through the voltages ($\underline{U}$) at connecting nodes. Then, the mapping function (f_1) is used to compute the normalized deviations of voltages ($\Delta\underline{U}^n$) as the main inputs to the ANN. Then, the ANN is used to define the corresponding normalized deviations of currents of the active components ($\Delta\underline{I}_a^n$). The complex power (P, Q) are calculated using the demapping function (f_2) and supplied to the external network.

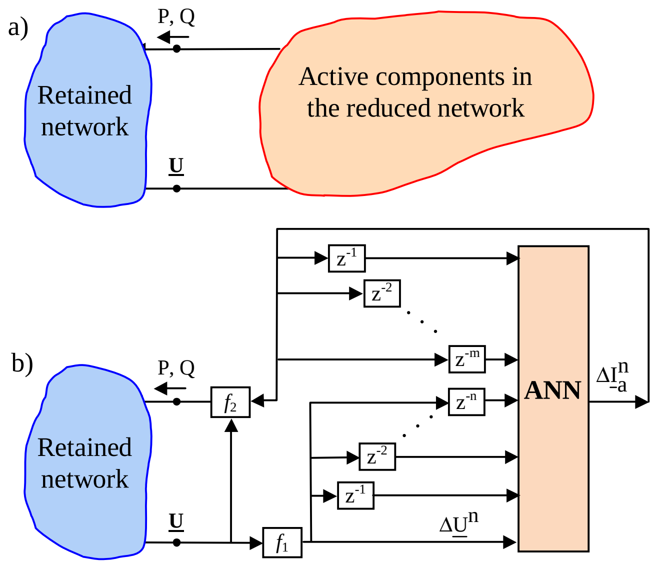


Fig. 1. Principles of the proposed dynamic equivalencing approach

III. Interconnected Test Power System

The proposed approach is applied to identify a dynamic equivalent for an 110-kV network and the underlying distribution systems in a 16-machine 380/220-kV-network. The network has three main areas and comprises 16 synchronous generating units with thermal, hydro and nuclear types. The 380-kV and 220-kV networks are modelled in detail with typical parameters. The one line diagram of the network, referred to as Power Stability Test network “PST16” [12], is shown in Fig. 2.

In this network, the 110-kV area (the shaded part in the figure) is extended to the low voltage level in a two step transformation staring from the six 110kV buses. As an intermediate step, the voltage is first transformed from 110 to 10kV using 6 transformers connected to the six 110kV buses and then to the 0.4kV level via distribution transformers. In the low voltage network, 56 end-user terminals are simulated with different load demand levels. A fuel cell and a micro-turbine, as two types of DG units, are placed near each load centre and connected to the load buses through 100-300m cables. This results in a total number of 112 DG sources of different types and capacities.

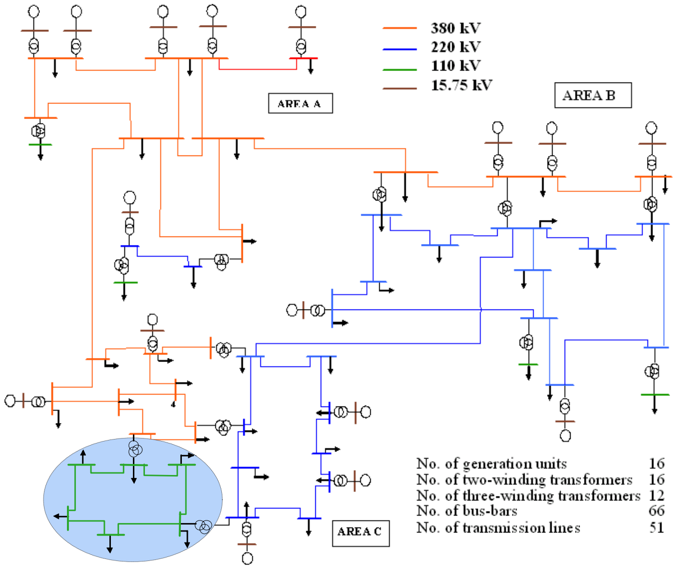
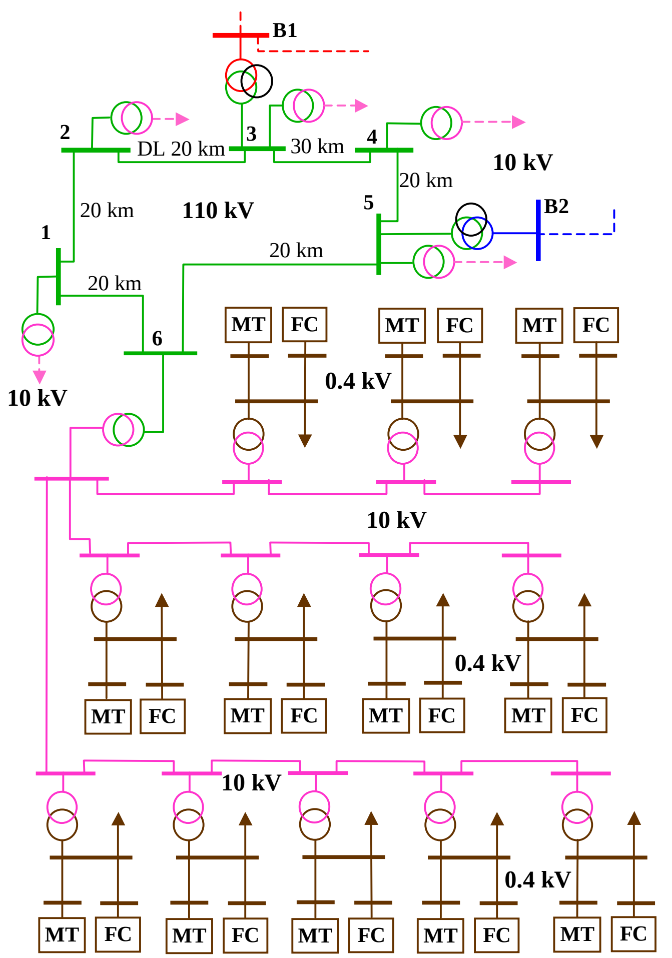


Fig. 2. The 16-machine test network PST16

Fig. 3 depicts the 110-kV section in addition to the medium and low voltage levels showing the integration of DG units into the load centres starting from one 110-kV bus. The other five-110kV buses have similar connection with the DG units.



Buses 1 to 5 are extended to the low voltage area with similar integration of Micro-Turbines (MT) and Fuel Cells (FC) like that shown for bus 6

Fig. 3. Modelling the medium and the low-voltage sections showing the integration of fuel cells and micro-turbines into the end user terminals

The micro turbines are simulated using the well-known equivalent block diagram model and interfaced with the network through cycloconvertes. On the other hand, a third order non-linear equivalent circuit is used to approximate the dynamics of the fuel cell. This model takes into account the steady state characteristics as well as the dynamic action of the unit. The steady state behaviour of the fuel cell is simulated through a non-linear resistance representing the voltage-current characteristics as can be obtained from the Nernest and Butler-Volmer equations. The dynamics of the unit include the delay actions in both the reformer and the stack in addition to the time constant associated with the current. All fuel cells are interfaced with the network through DC-AC PWM inverters. Suitable controllers are developed with each unit to regulate its performance.

Different types of fuel cells are used including proton exchange membrane, alkaline and solid oxide fuel cells. Also, various capacities of fuel cells and micro-turbines are simulated. In a previous work [2], the detail dynamic models of fuel cells and micro-turbines are presented. This previous study aimed to highlight the dynamic performance of these DG units within a multi-machine network and the interaction between DG units and the high voltage network. In large interconnected systems, where the number of elements in the distribution system may reach up to thousands of units, the detailed simulation of all elements is unfeasible. The current research attempts to develop a dynamic equivalent for this part of the network, which comprises a large number of active components. Replacing this area by suitable dynamic equivalent would simplify the modelling and simulation analysis considerably. However, conventional lumped-load representation of distribution system will be misleading when active DG sources are spread within power systems. The power generated from these sources will impact the performance of the entire network and hence, their effect has to be taken into account. In the network under consideration, the power from active DG units reaches up to 30% of the total load demand in the low-voltage area. The 110kV system as well as the medium and low voltage networks including the DG units (see Figs. 1 and 2) are to be replaced by the ANN-based dynamic equivalent in addition to lumped equivalent loads at boundary buses. The remaining part of the high-voltage network is retained for further detailed simulation and analysis. There are two interconnecting buses serving as the interfaces between the two subsystems (B1 and B2 shown in Fig. 3). Measurements only at these two boundary buses are required to develop the ANN-based dynamic equivalent model.

IV. Recurrent ANN for Dynamic Equivalents

The recurrent ANN is trained by time series depending on a number of three-phase short circuits simulated at different locations in the retained network. The simulation is carried out for 15s with 5ms integration time step. The modelling and simulation of the full system, and also the reduced one, are accomplished using the simulation package "*Power System Dynamics* (PSD)" [13]. Voltage and current waveforms at boundary buses are used to prepare suitable patterns for training the ANN.

The structure of the ANN depends on the conventional feedforward configuration with a time history of variables involved in the input features to the network. This can be an alternative to the real recurrent arrangement in the training process, which facilitates the training process. However, when implementing the dynamic equivalent model in the simulation program it will interact with the external network depending on real recurrent loops. Since the ANN has to capture dynamics from both retained and replaced subsystems, recurrent loops from voltages, as decision variables from the retained network, and currents, as decision variables from the equivalent system, are required. Therefore, past values of both normalized voltage and current deviations are used at the input layer of the ANN.

With two boundary buses, the ANN has 4 main inputs, representing the real and imaginary components of normalized deviations of boundary-bus voltages. Also, the ANN has four outputs, which are the real and imaginary components of normalized deviations of injected currents. Furthermore, normalized deviations of voltages and currents at four previous time intervals are received at the input nodes of the network in the training process. The ANN contains two hidden layers with 10 and 5 neurons in the first and the second hidden layers respectively. All hidden layers comprise neurons with nonlinear-sigmoid activation functions, while neurons in the output layer have linear functions. After training the ANN, the parameters (biases and weights) are saved to be used in the implementation procedures.

V. Implementation of the ANN-Based Equivalent

In this section, the integration of the ANN-based dynamic equivalent with the simulation package PSD is explored. Since the equivalent model is intended for online applications, it has to be implemented in such a way that it interacts with the retained subsystem at each time step to give similar behaviour like that of the original network.

In the PSD package, the conventional elements in power system (such as generators, transformers...etc) are simulated by selecting the appropriate model and giving the suitable parameters. It is also possible to describe controllers and unconventional energy sources in a so-called "regulator files". In these files, a complete description of the dynamic behaviour of the elements can be stored and integrated into the network through one or more buses. At each time step, state variables (voltage, currents...etc) are captured and processed within the file and finally, the corresponding outputs are computed and supplied to the external network. The processing within the regulator files is accomplished using pre-constructed blocks.

A block simulating the behaviour of the ANN can be used within the regulator files after defining the inputs to the ANN, with recurrent loops if required. All information about the ANN structure (such as biases, weights and types of activation functions) are saved in a supplementary text file to be used through the simulation process. The outputs from the ANN are then used with other variables to calculate the complex powers, which will be supplied to the external network. Fig. 4 gives an idea about implementation and interaction of the ANN-based dynamic equivalent with the retained network.

At each time interval, the instantaneous values of boundary-bus voltages are used in the regulator file to compute the normalized voltage-deviations through the function (f_1). The normalized voltage deviations are processed with previous normalized current and voltage deviations to calculate the present normalized current deviations using the ANN. The active and reactive powers are computed using the function (f_2) and supplied to the network.

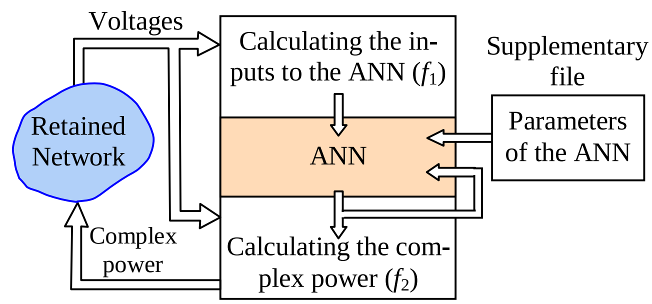


Fig. 4. Implementation and interaction of the ANN-based dynamic equivalent with the retained network

VI. Simulation Results and Discussion

After implementing the ANN-based dynamic model, the performance is investigated online and the behaviour is compared with that of the full system. Fig. 5 shows a comparison between the two systems after simulating a 3-phase short circuit in the high voltage system.

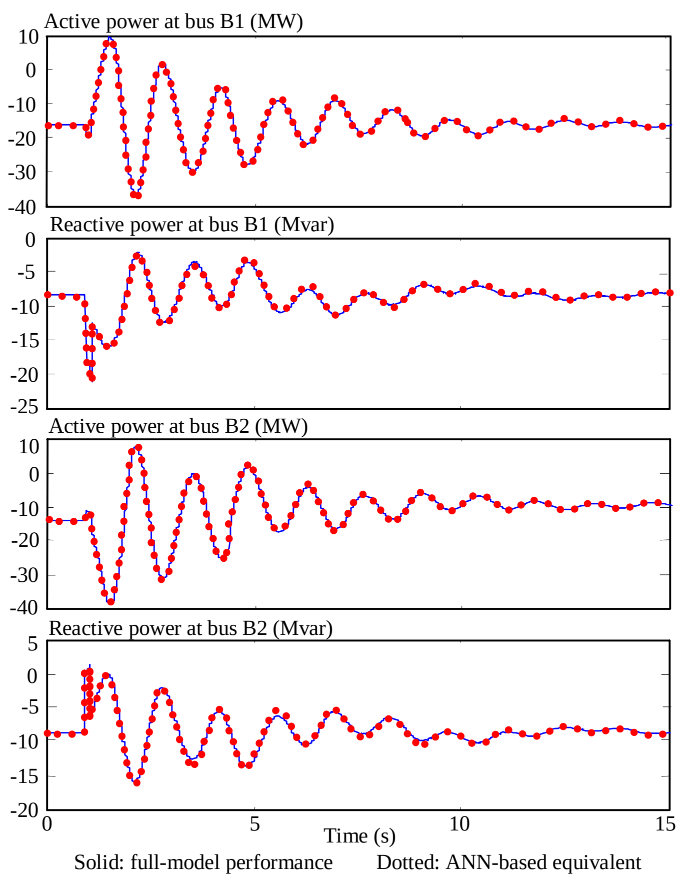


Fig. 5. A comparison between the performance of full-model and equivalent model under a disturbance, which is not used in the training process

The total equivalent complex power supplied *to* all active units in the distribution system through each boundary bus is illustrated. The negative sign of "steady state" values indicates that the power is flowing *out* of the sources (consumer oriented sign convention). It is important to notice that this fault was *not* used in preparing the patterns for training the ANN. The similarity between the obtained responses is obvious, which means that the recurrent ANN is robustly successful in capturing the target waveforms. Similar comparisons are carried out under several other disturbances, where the performance is always similar to that of the original complete model. This ensures that the ANN-based model effectively reproduces the behaviour of the replaced subsystem in a general form. Therefore, different studies of the entire network including the proposed equivalent model are possible with high accuracy.

To demonstrate the capability of the presented equivalent model over a wide range of operating conditions, the behaviour of the same equivalent model are studied under new power-flow conditions by varying the loading conditions in the retained network. The generated power and load demand in the replaced subsystem is maintained constant. Therefore, the total power transferred from the retained system to the low-voltage network is not changed. However, the voltages and the partition of the power at the two boundary buses are changed as shown in Table 1. The total power transferred is slightly increased to account for the increase in the power loss due to the voltage reduction.

Table 1. Voltages and powers at boundary buses for the base and the new power-flow cases

	U_1 (kV)	U_2 (kV)	S_1 (MVA)	S_2 (MVA)
Base case	381.15	222.53	54.82+j15.31	22.33+j3.26
New case	378.34	221.42	61.43+j13.41	15.84+j5.95

A new three-phase short circuit is simulated in the high-voltage network using the new initial conditions and then the performances of the full and the reduced models are studied. Fig. 6 shows a comparison between the powers supplied by active units through the two boundary buses, where the results from the equivalent model are still in good agreement with the full system. The use of normalized deviations rather than the variables themselves extends the validity of the dynamic equivalent to cover new initial conditions with high accuracy.

Most of the conventional dynamic equivalents fail to simulate the performance of the entire network if any change occurs inside the replaced system. The simulation of the new condition requires the development of a new dynamic model. This is not the case with the proposed dynamic equivalent due to the modelling of active components separately from the passive loads in addition to normalizing the decision variables. To examine the validity of the equivalent model under new generating conditions in the replaced network, the power from the active sources in the low-voltage area is decreased to about 50% of its original value. This is accomplished by switching off some of these units in the full-system model. In the equivalent model, the change of the power is carried out by modifying the initial values of currents and voltages in the functions (f_1) and (f_2).

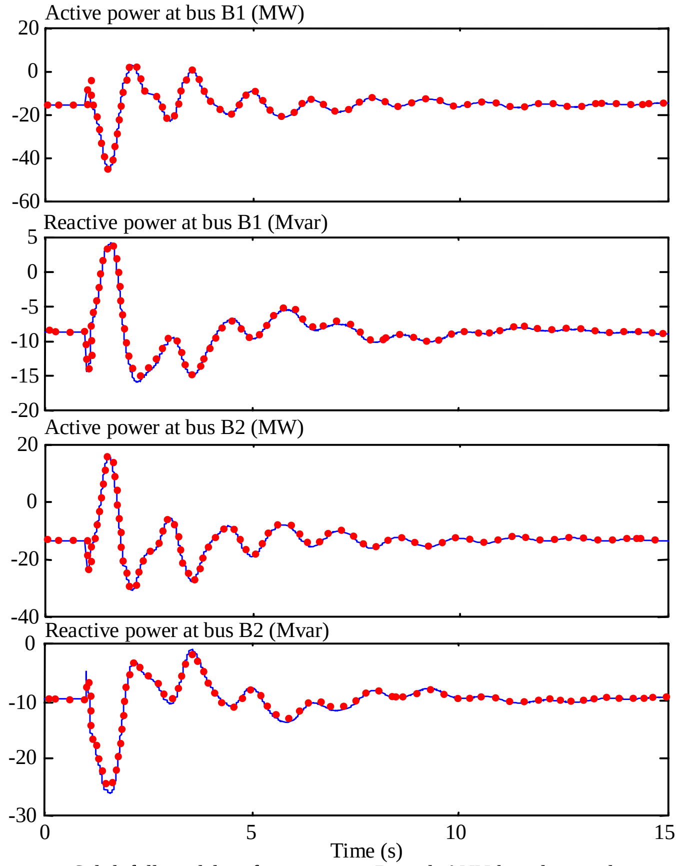


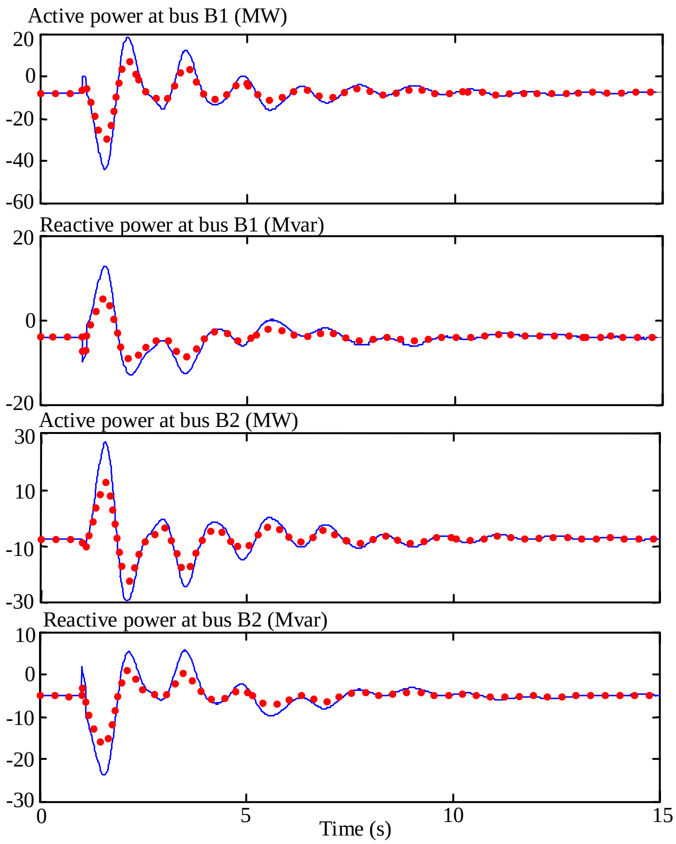
Fig. 6. A comparison between the full-model and the equivalent systems starting from a new power-flow initial condition

Table 2 gives the new contribution of active sources at each boundary bus under the new generating conditions in the distribution system. The loading conditions in the retained network as well as in the distribution system are held constant in the new case.

Table 2. The new loading conditions of the active units in the replaced network

	Power portion from active sources at the two boundary buses (MVA)	
	through bus B_1	through bus B_2
Base case	15.86+j8.28	13.85+j9.29
New case	8.30+j4.24	7.57+j4.95

After changing the power contribution of the active sources in the distribution system, a three-phase short circuit is introduced into the retained network. Fig. 7 illustrates a comparison between the total power of active units using the full model and the equivalent model following this fault. The comparison shows a reasonable accuracy even with the large change (50%) inside the replaced network. This confirms the universality of the proposed approach as no modifications in the structure or parameters of the ANN-based dynamic model are necessary. This advantage is very important due to the regular variation in the switching status of the DG units. Therefore any equivalent model for distribution systems has to be flexible enough to consider the potential variations in the power supplied by the DG sources.



Solid: full-model performance   Dotted: ANN-based equivalent

Fig. 7. A comparison between the full-model and the equivalent systems after changing the power of the DG sources in the distribution system

VII. CONCLUSIONS

The paper presents a new ANN-based approach for dynamic equivalencing of distribution networks with dispersed generation. Distributed generation units such as fuel cells and micro turbines are expected to feature prominently in distribution networks in the near future, and any realistic dynamic model of a distribution system under these circumstances needs to take into account the effect of these units on the dynamics of the high voltage network. The proposed technique is based on recurrent ANN and requires simulation results or measurements only at the boundary buses. The equivalent dynamic model thus obtained was implemented on a power system simulation package to investigate whether the model is capable of reproducing the dynamic behaviour of the replaced network in full. The results demonstrate the capability of the equivalent model to capture the dynamic behaviour of the replaced network in its entirety. The model provided outstanding conformity with the results obtained using the full dynamic model of the network even under new generation and loading conditions. The approach promises a significant simplification of the dynamic analysis of large interconnected networks.

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IX. BIOGRAPHIES

Ahmed M. Azmy (1968) was born in El-Menoufya, Egypt. He received the B.Sc. and M.Sc. degrees in electrical engineering from the El-Menoufya University, Egypt in 1991 and 1996, respectively. Since 1992, he has been with the Power Engineering and Electrical Machines Department, Faculty of Engineering, University of Tanta, Egypt. He started his Ph.D. in the university Duisburg-Essen, Germany in 2001 supported by an Egyptian government scholarship. His Ph.D. thesis focuses on the Modelling and Intelligent management of Interconnected Decentralized Power Generating units.

Istvan Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and IEEE