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MODELING AND VERIFICATION OF A REDUCED NETWORK IN REAL-TIME SIMULATOR

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Abstract- As the power systems have evolved in technology and the complexity of the systems has increased in recent years, their needs have also increased. Among the approaches that arise are the implementation of special protection systems (SPSs) that ensure the continuity of the system. On the other hand, avoiding put at risk of system security by making unexpected mistakes that may occur during design studies of protection systems, is critical. Real-time simulation platform is effective method in testing protection systems. In this paper, the northeastern region of Turkish electricity grid is modeled, and then the verification of model is performed with different studies for SPS hardware tests.

Keywords: Power System Modeling, Verification, Real-Time Simulation, Network Reduction, Special Protection System, Transient Stability.

I. INTRODUCTION

As being one of the most efficient way to transport the energy produced by different resources, electricity power system is today's indispensable utility to continue the developed civilizations in all around the world. In order to compete with exponential development in technology, electricity grids should be reinforced to achieve the highest supply quality as possibly. However, it is not easy to maintain both security of supply and quality of service as expected. In northeastern part of Turkish grid, a special protection system (SPS) is sought in order to coordinate the outages around the region; hence, reducing the risk of regional brownout.

Special protection systems are designed to ensure power system security during abnormal conditions and contingencies [1]. Furthermore, the utilization of SPS in the region will enable to monitor system conditions in *n* and *n*-1 conditions, hence will provide prevention from cascaded outages that may result in a regional system blackout via initiating a series of pre-planned shedding actions.

Although the special protection systems are designed to maintain stable and reliable power system operation, their application introduces several risks. In order to minimize the operational complexity and relieve the system operator, the design should be simple as much as possible. Additionally, SPS should has minimum elements to increase reliability. To ensure the reliability of such systems, several tests should be conducted before installation. Testing on site is neither practical nor safe way to examine stability, accuracy and dependability of these systems.

Besides, that may endanger system operation. Hence, the prepared system should be tested on add-on hardware before installation. One of the most common methods is real-time hardware in the loop (HIL) simulations, in which the power system can be modeled in real time in the virtual environment and simulate with an external hardware [2]. Real-time HIL simulation testing answers the questions about behaviors of power system protection devices.

In recent years, the cost of real-time simulation systems has been reduced with the increase in usage. With the exponential rate of increase of electronic and software technologies, however, it is possible to create and implement real-time simulation models of large-scale power systems [3].

The objective of this paper is modeling and verification northeastern part of Turkish electricity grid in real-time simulator. Main purpose of the studies is preparation of SPS hardware tests. Therefore, being close to reality very important for the validity of the tests to be performed after modeling the system.

II. INFORMATION ABOUT ANALYZED NETWORK DATA

Turkish Electricity Transmission Company (TEIAS) is responsible for the operation of 400 kV and 154 kV transmission lines in Turkish grid. The total length of the 400 kV and 154 kV transmission lines in Turkish grid is 18600 km and 40500 km long, respectively [4].

The current grid topology is used during the real-time system modeling studies. Dispatcher Information System (YTBS) [5] database is used as a source for modelling network topology. Additionally, investment plans which are announced by Turkish Grid Operator (TEIAS) are added to system topology to model expected grid exactly.

III. METHODOLOGY

It is not practical to model entire electricity network for real time simulation as it necessitates greater computational capacity to the simulator. In such a case, network reduction, that focuses the SPS implementation area, is made to reduce computational burden for the real time simulation. In other words, the region to be analyzed is modeled in detail (internal area), and the rest of system model modeled as equivalent.

The reduction is conducted providing that the system behavior shows similar static and dynamical responses as the full model. In order to create such equivalency, an extended ward equivalent approach is made together with remaining system inertial model.

MATLAB/Simulink software is used detailed modeling northeastern part of Turkish grid for real-time HIL simulation. While the static system components (transformers, generators, transmission lines etc.) are modeled using Simulink *simpowersystems* and the Opal-RT Artemis library.

After creation of the real-time simulation, it is distributed to the processors of the simulator proportionally. In the last stage, verification studies of the reduced real-time simulator model are performed.

IV. MODELING OF NORTHEASTERN PART OF TURKISH GRID

As illustrated in Figure 1, the Turkish electricity grid is divided into an internal system covering the northeastern region where the relevant analyzes are to be carried out and an external system including the remaining part of the Turkish electricity grid.

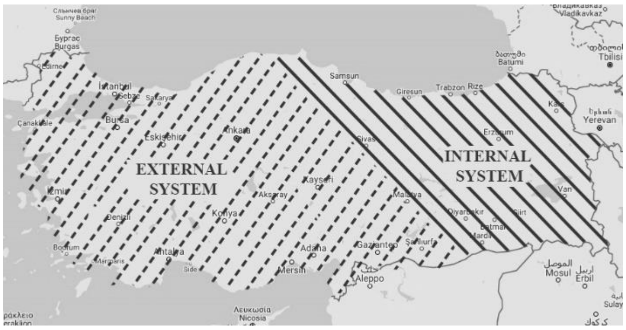

Figure 1. Defined internal and external systems

The internal and external zones are decided according to the analyses of SPS design studies. Although the special protection system will work on the A-E-H corridor shown in Figure 2. The internal system has been enlarged since the considerable effect of the nearby busbars, transmission lines and generators on the analysis.

A. Northeastern Part of Turkish Grid

Power generation is larger than electricity consumption in northeastern part of Turkish grid. Especially in spring and summer, with increasing flow rate of rivers, electricity surplus of the area dramatically increases. Additionally, there is HVDC B2B connection with Georgia where important amount of electricity import is planned.

This leads to increase current carried in electricity transmission corridors connected Northeastern part of the grid to the western part of Turkish Grid where major consumption is made. However, northeastern region is mainly tied via two 400 kV corridor as shown in Figure 2. Note that two main transmission corridors, E-A and E-H 400 kV corridors. It should be noted that these two main corridors have a limited capacity and transmission bottlenecks in the region is expected.

System stability studies has shown that during some critical contingency conditions on 400 kV grid, may lead loss of dynamic stability. It is clear that loss of a corridor leads the redirection of huge amount of flow to another corridor. Meanwhile, the impedance and angle difference between eastern and northern of Turkish Grid increases dramatically.

The majority of the 400 kV and 154 kV grid-connected power plants in the region are HPPs and NGCCPPs. Generators, transformers and shunt capacitors are modeled with generic models of *simpowersystem* library. System parameters for transmission lines, generators and transformers are obtained from the system operator.

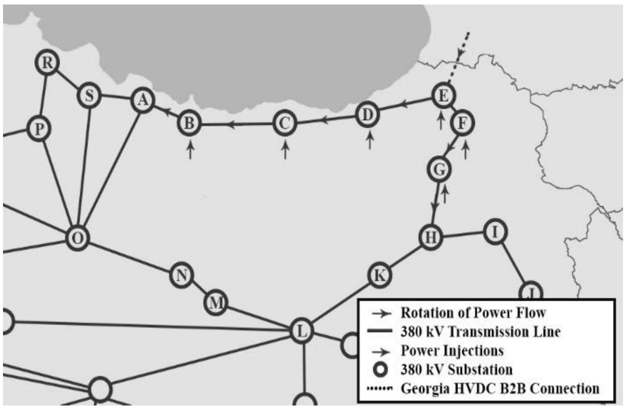

Figure 2. Northeastern part of Turkish grid

B. Modelling of System Dynamic Controllers

In order to obtain system dynamics behavior during fault and contingency conditions, it is necessary to model the dynamic controllers (AVR, PSS etc.) in generation plants. There are approximately 154 power plant units at different power levels in internal system. Dynamic components such as excitation systems and power system stabilizers of large plants that can affect system stability are modeled. AVR models, used in dynamic models are below.

- BUDCZT (Czech proportional/integral ESM)
- ESST1A (1992 IEEE type ST1A ESM)
- EXST1 (1981 IEEE type ST1 ESM)
- URST5T (IEEE proposed type ST5B ESM)

PSS2B (IEEE dual-input stabilizer) model is used as the power system stabilizer model in the related power plants. The dynamic modelling approach shown in Figure 3 is utilized.

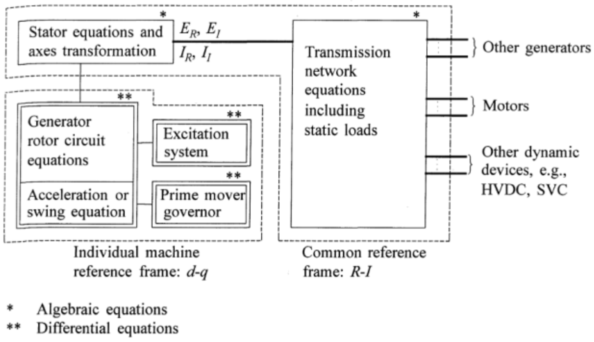

Figure 3. Power system model for transient stability analysis [6]

There are many run of the river hydroelectric power plants on small scales in the region. These power plants are operated only in PQ (Constant active and reactive power) mode and have no effect for voltage regulation. Therefore, it is not necessary to model the dynamic controllers of all these plants.

V. MODELING EXTERNAL PART OF SYSTEM

A. Generators Aggregation

The coherence approach method was used while creating the external system equivalent. Coherency means that a group of generators acts as a single aggregated machine against a disturbance that occur far away [7]. Coherency technique can be taken up in 5 procedures.

- Divide the system into internal and external system.
- Assume a large disturbance inside the internal system and identify the coherency generators in external system.
- Aggregate those coherency generators as one.
- Reduce the topologic of the network system.
- Obtain the reduced system and calculated parameters

In order to determine the behavior of the coherent generator group, stability analyses are carried out for both reduced model and full model. After identification of the coherent generator group as explained above, the generators in the same group is aggregated as a single equivalent generator. Thus, the parameters of the equivalent generator are listed below. The inertia of the equivalent generator is:

$$M^* = \sum_{i=1}^{n} M_i \tag{1}$$

The damping coefficient of the equivalent generator is:

$$D^* = \sum_{i=1}^{n} D_i \tag{2}$$

In the motion equation of generator rotor, the electrical power also can be represented as:

$$P_{ei} = \frac{E_i' U_i}{\sum x_i} \sin \delta_i \tag{3}$$

The $\sum x_i$ is the summary of the generator impedance which contents the transient impedance X_d'. Thus, the transient impedance of the equivalent generator is:

$$X_d'^* = \frac{1}{\sum_{i=1}^{n} \frac{1}{X_d'}} \tag{4}$$

Finally, the three main parameters inertia, damping coefficient and transient impedance are aggregated to establish the equivalent generator [8].

B. Power Network Topology Reduction

After aggregation of the coherent generators, the remained busbars and transmission lines connected between also need to be reduced. The topological reduction method is required. The external system has to be divided two parts, the remaining and the eliminated part. Gauss elimination method is used for eliminating the part which doesn't contain equivalent generators [8].

$$\begin{bmatrix} \dot{I}_R \\ \dot{I}_E \end{bmatrix} = \begin{bmatrix} \dot{Y}_{RR} & \dot{Y}_{RE} \\ \dot{Y}_{ER} & \dot{Y}_{EE} \end{bmatrix} \begin{bmatrix} \dot{V}_R \\ \dot{V}_E \end{bmatrix} \tag{5}$$

$$\dot{I}_R = \left(\dot{Y}_{RR} - \dot{Y}_{RE} \dot{Y}_{EE}^{-1} \dot{Y}_{ER} \right) \dot{V}_R + \dot{Y}_{ER} \dot{Y}_{EE}^{-1} \dot{I}_E \tag{6}$$

By using (5) and (6) equations the equivalence injection power can be obtained. This aggregated method is based on all the elements can be represented as constant impedance.

DIgSILENT PowerFactory *network reduction tool uses the coherence approach method and the topological reduction method while creating new reduced network [11]. The power flows between boundary substations are calculated as impedances. Load flow, short circuit and stability calculations of external grid is modelled as extended ward equivalent. At first second of simulation, a three-phase fault that lasted 150 ms is executed at middle of D-E 400 kV transmission line. Before and after reduction operation of external grid by using DIgSILENT PF network reduction tool, angle difference curves between E-A and E-H substations are illustrated as Figures 4 and 5*

Figure 5, respectively. For same event voltage curves of A-E and H substations before and after reduction operation are illustrated as Figure 6.

Equal external system calculation parameters which calculated by DIgSILENT *PF* network reduction tool are used for assumptions of MATLAB/Simulink real-time simulator model. Calculated equal inertia of external grid is divided to two aggregated generators and connected two main boundary substations.

Due to low effect on transient stability analyses and calculation constraints of real-time simulator, there is no need to model the power flows between boundary substations. To ensure steady state conditions of simulation, power flows between boundary substations are modelled as dynamic load.

C. Aggregation of Generator Controllers

Most of generators have dynamic controllers (etc. AVR, PSS and Governor) in external grid. Hence, equal dynamic controller parameters of aggregated generator have to be calculated. Calculation operation of equal dynamic controller parameters is theoretically possible. Even if possible, this method is not preferred because of complexity of functions.

The dynamic controller model and parameters used in the aggregated generator is calculated by empirical method. After creation of real-time simulator equal external grid model, same fault event is executed in section B. Angle difference curves between E-A and E-H substations are illustrated as Figures 4 and 5, respectively. At the same event, voltage curves of A-E and H substations before and after reduction operation are illustrated as Figure 6.

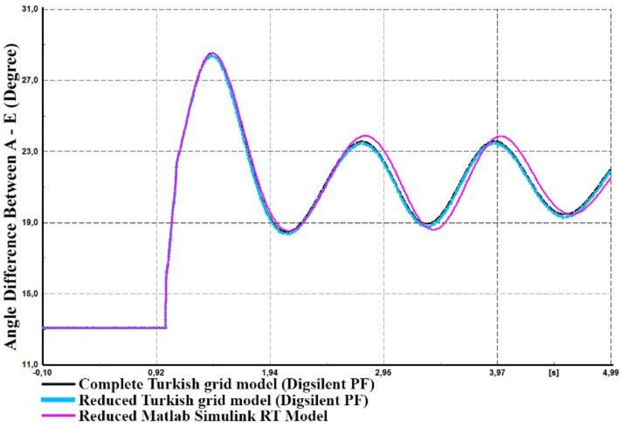

Figure 4. Comparison of angle difference curves between A-E Substations

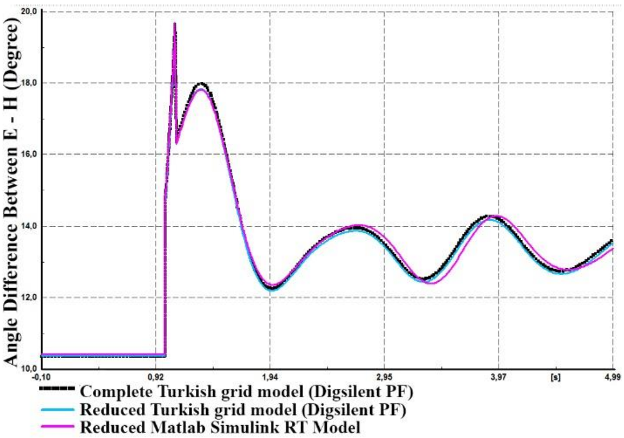

Figure 5. Comparison of angle difference curves between E-H Substations

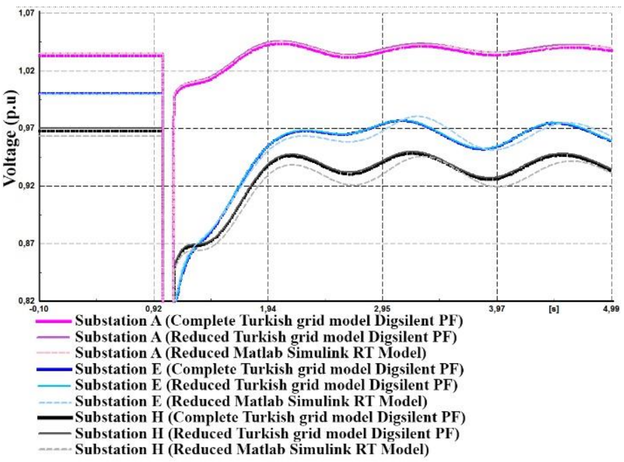

Figure 6. Comparison of substation voltage curves

D. B2B HVDC Connection

As explained, there is a HVDC B2B connection between the Turkey and Georgia in the focused modelling area. It is not possible to fully model the HVDC control behavior in the real time simulation model, hence; a simple engineering assumption is made. The dynamic behavior of this connection can be approximated as of a constant power load dynamic behavior assuming that the any commutation failure will not take place in the HVDC. In order to show this several dynamical studies are made.

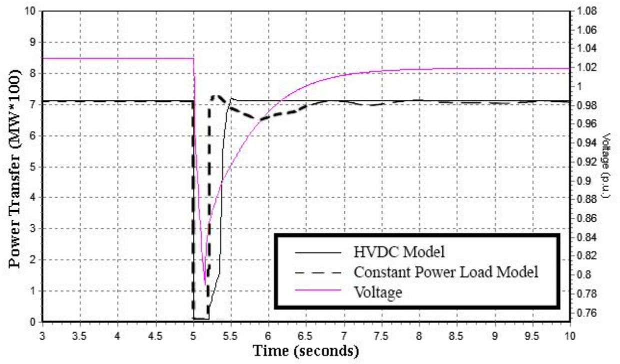

Figure 7. Comparison of HVDC and constant load model behaviors [1]

As illustrated in Figure 7, a three phase fault close to HVDC block at t=5 second is applied and is cleared after 150 ms. On the other hand, the same process is repeated using the constant power load model instead of the HVDC model and the results are compared in Figure 7. Comparison of curves shows that the dynamic behavior of HVDC model can be approximated as a constant power load model.

VI. REAL-TIME SIMULATOR MODEL

Opal-RT OP5600 (ML605 board) is a scalable, flexible platform that modelling studies are carried out on this platform. Opal-RT provides tools to separate the system model into subsystem models that can be executed on parallel target processors. Opal-RT Real-Time Laboratory (RT-LAB) is used as an interface software. The generated model was compiled into executable code and executed on RT-LAB platform via several parallel processors [9].

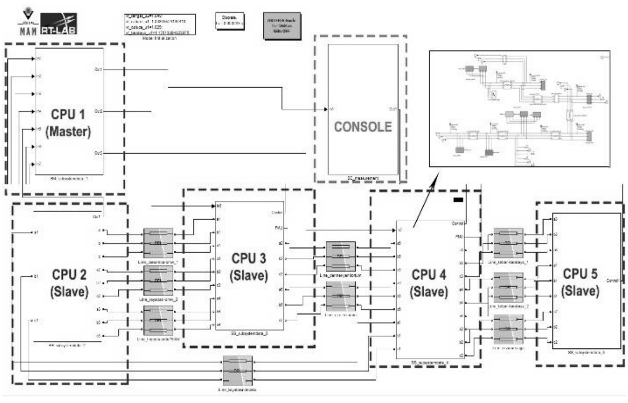

Figure 8. Real-time simulation model of northeastern part of Turkish grid

In a real-time simulation, the calculation effort at every step must be kept within the fixed boundaries of the corresponding real-time interval. The network topology is designed to meet this demand and separated into 5 fundamental parts. Every parts of network are embedded in different CPUs for parallel calculation. As illustrated in Figure 8, model (plants, transmission lines, transformers, breakers) is built into 4 slave subsystems and dynamic controllers, are built into master subsystem.

Considering propagation delay of the transmission lines the time step for the overall simulation system is set as 268 μs [10]. For the SPS hardware real-time HIL tests the Backward-Euler integration rule is used with the reason that excellent stability characteristics associated with the Backward-Euler method. Initial condition parameters of real-time simulation (for custom dynamic models PSS, AVR etc.) is determined by load flow block of MATLAB/Simulink. The determined initial condition parameters are defined in model initialization block to run real-time simulation in a steady state condition.

VII. RESULTS

Verification is performed by comparing the behavior of detailed dynamical simulation model of the Turkish network in DIgSILENT PF simulation environment and MATLAB/Simulink real-time simulation model which includes the explained reductions and assumptions. In this regard, dynamical system behaviors of these models are compared in several operation scenarios. Figures from 9-14 show the comparison results of phase angles, terminal voltages and load changes in one of the busbars in the system model.

In the first scenario, at fifth second of the simulation a three-phase fault that lasted 120 ms is executed at middle of the E-F transmission line. The angle difference results is shown in Figure 9, voltage results is shown in Figure 10 and active power results is shown in Figure 11.

In the second scenario, at fifth second of the simulation a three-phase fault that lasted 120 ms is executed at middle of the B-C transmission line. The angle difference results is shown in Figure 12, voltage results is shown in Figure 13 and active power results is shown in Figure 14.

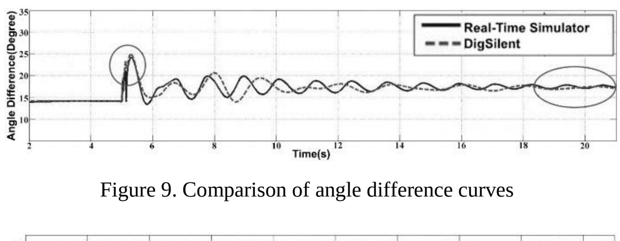

Figure 9. Comparison of angle difference curves

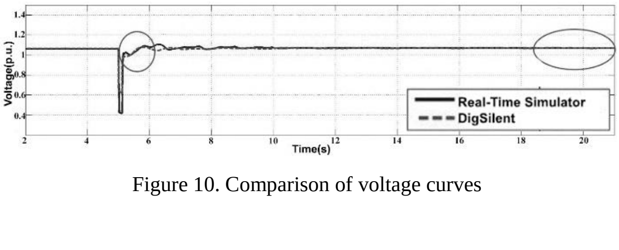

Figure 10. Comparison of voltage curves

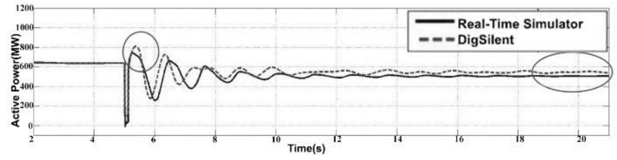

Figure 11. Comparison of active power curves

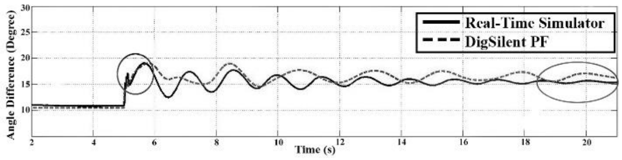

Figure 12. Comparison of angle difference curves

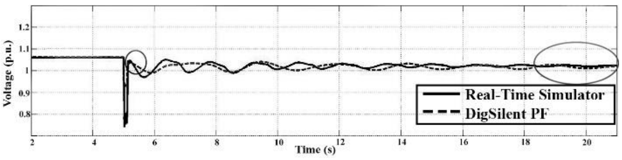

Figure 13. Comparison of voltage curves

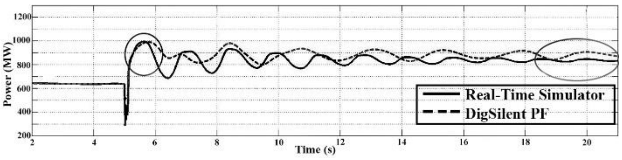

Figure 14. Comparison of active power curves

The results of the comparison studies imply that the created real time model shows similar behavior with the full grid model. This yields that the real time simulation model can be satisfactorily utilized during SPS hardware in the loop simulations.

VIII. CONCLUSION

This paper reported modeling and verification studies of northeastern part of Turkish grid in real-time simulator. An equivalent system is created taking into account the calculation constraints of the real-time simulator. Comparison of result curves shows that the dynamic behavior of equivalent real-time simulator model and comprehensive Turkish grid model are close to each other.

NOMENCLATURES

A. Acronyms

HVDC: High Voltage Direct Current
B2B: Back to Back
AVR: Automatic Voltage Regulator
HPP: Hydroelectric Power Plant
SPS: Special Protection System
PSS: Power System Stabilizer
NGCCPP: Natural Gas Combined Cycle Power Plant

B. Symbols / Parameters

E_i' : Transient electromotive force
U_i : Generator terminal voltage
δ_i : The power factor

$\dot{I}_R$: The injection current vector of the remained node
$\dot{I}_E$: The injection current vector of the eliminated node
$\dot{V}_R$: The voltage vector of the remain node
$\dot{V}_E$: The voltage vector of the eliminated node
$\dot{Y}_{RR}$: The self-admittance of the remained system
$\dot{Y}_{EE}$: The self-admittance of the eliminated system
$\dot{Y}_{RE}$: The mutual-admittance of the remaining system
$\dot{Y}_{ER}$: The mutual-admittance of the eliminated system

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BIOGRAPHIES

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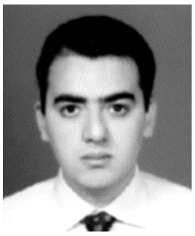

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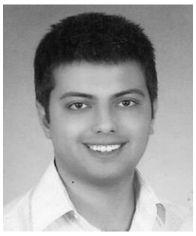

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