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Dynamic equivalence by an optimal strategy

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ABSTRACT

Due to the curse of dimensionality, dynamic equivalence remains a computational tool that helps to analyze large amount of power systems' information. In this paper, a robust dynamic equivalence is proposed to reduce the computational burden and time consuming that the transient stability studies of large power systems represent. The technique is based on a multi-objective optimal formulation solved by a genetic algorithm. A simplification of the Mexican interconnected power system is tested. An index is used to assess the proximity between simulations carried out using the full and the reduced model. Likewise, it is assumed the use of information stemming from power measurements units (PMUs), which gives certainty to such information, and gives rise to better estimates.

1. Introduction

One way to speed up the dynamic studies of currently interconnected power systems without significant loss of accuracy is to reduce the size of the system model by means of dynamic equivalents. The dynamic equivalent is a simplified dynamic model used to replace an uninterested part, known as an external part, of a power system model. This replacement aims to reduce the dimension of the original model while the part of interest remains unchanged [1–6].

The phrases "Internal system" (IS) and "external system" (ES) are used in this paper to describe the area in question, and the remaining regions, respectively. Boundary buses and tie lines can be defined in each IS or ES. It is usually intended to perform detailed studies in the IS. However, the ES is important to the extent where it affects IS analyses.

The equivalent does not alter the transient behavior of the part of the system that is of concern and greatly reduces the dimension of the network, reducing computational time and effort [4,7,8]. The dynamic equivalent also can meet the accuracy in engineering, achieving effective, rapid and precise stability analysis and security controls for large-scale power system [4,8]. However, the determination of dynamic equivalents may also be a time consuming task, even if performed off-line. Moreover, several dynamic equivalents may be required to represent different operating conditions of the same system. Therefore, it is important to have computational tools that automate the procedure to evaluate the dynamic equivalent [7].

Ordinarily, dynamic equivalents can be constructed following two distinct approaches: (i) reduction approach, and (ii) identification approach. The reduction approach is based on an elimination/aggregation of some components of the existing model [4,5,9]. The two mostly found in the literature are known as modal reduction [6,10] and coherency based aggregation [2,11,12]. The identification approach is based on either parametric or non-parametric identification [13,14]. In this approach, the dynamic equivalent is determined from online measurements by adjusting an assumed model until its response matches with measurements. Concerning the capability of the model, the dynamic equivalent obtained from the reduction approach is considerably more reliable and accurate than those set up by the identification approach, because it is determined from an exact model rather than an approximation based on measurements. However, the reduction-based equivalent requires a complete set of modeling data (e.g. model, parameters, and operating status) which is rarely available in practice, in particular the generators' dynamic parameters [5,13,15,16].

On the other hand, due to the lack of complete system data, and/or frequently variations of the parameters with time, the importance of estimation methods is revealed noticeably. Especially, on-line model correction aids for employing adaptive

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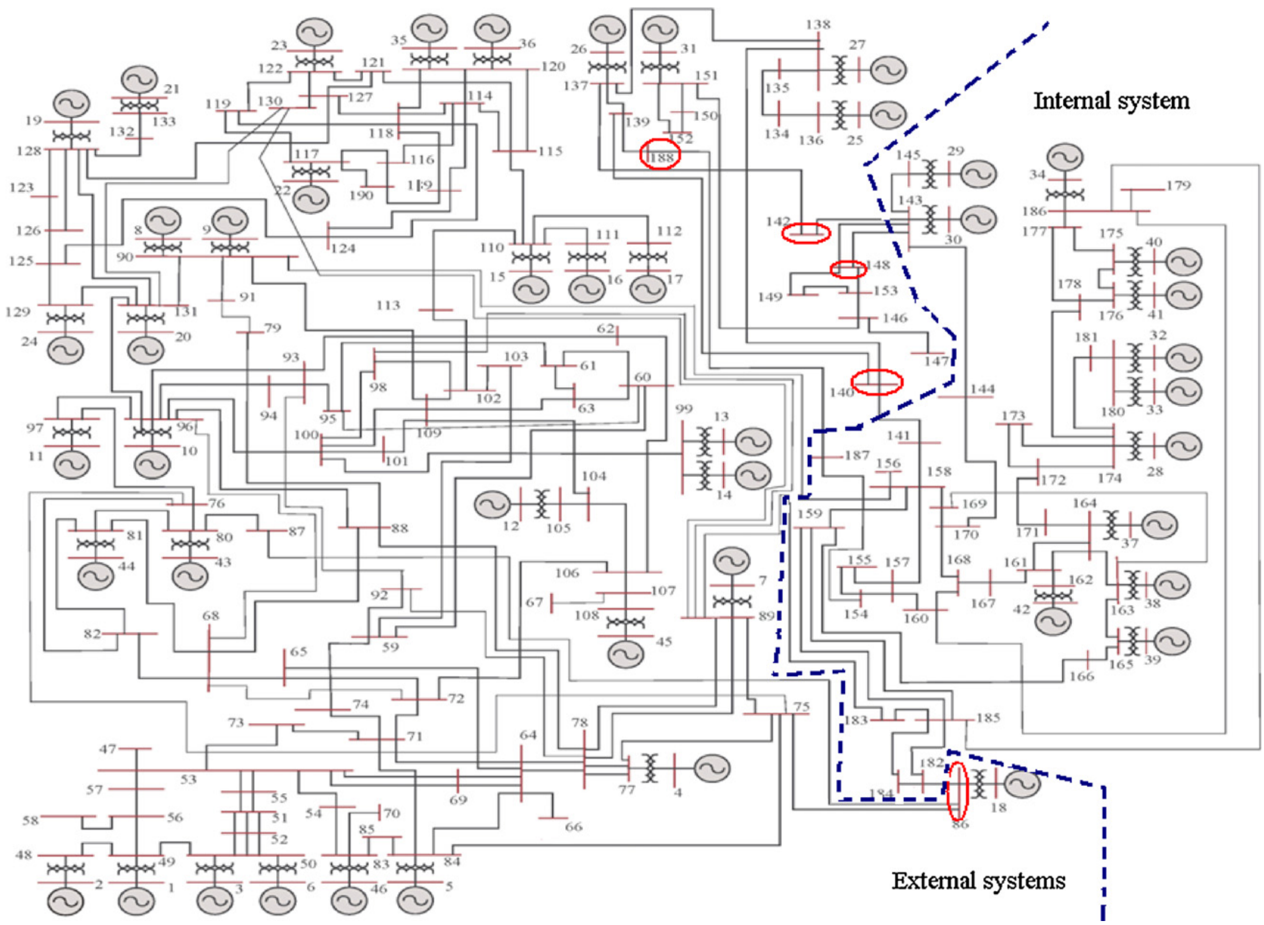

Fig. 1. 190-buses 46-generators power system.

controllers, power system stabilizers (PSS) or transient stability assessment. The capability of such methods has become serious rival of the old conventional methods (e.g. the coherency [11,12] and the modal [6,10] approaches). The equivalent estimation methods have spread, because it can be estimated founded on data measured only on the boundary nodes between the study system and the external system. This way, without any need of information from the external system, estimation process tries to estimate a reduced order linear model, which is replaced for the external part. Evidently, estimation methods can be used, in presence of perfect data of the network as well to compute the equivalent by simulation and/or model order reduction [15].

Sophisticated techniques have become interesting subject for researchers to solve identification problems since 90s. For example, to obtain a dynamic equivalent of an external subsystem, an optimization problem has been solved by the Levenberg–Marquardt algorithm [17]. Artificial neural networks (ANN) are the most prevalent method between these techniques because of its high inherent ability for modeling nonlinear systems, including power system dynamic equivalents [15,18–25].

Power system real time control for security and stability has promoted the study of on-line dynamic equivalent technologies, which progresses in two directions. One is to improve the original off-line method. The mainstream approach is to obtain equivalent model based on typical operation modes and adjust equivalent parameters according to real time collected information [4]. Distributed coordinate calculation based on real time information exchanging makes it possible to realize on-line equivalence of multi-area interconnected power system in power market environment [4]. Ourari et al. [26] developed the slow coherency theory based on the structure preservation technique, and integrated dynamic equivalence into power system simulator Hypersim, verifying the feasibility of on-line computation from both computing time and accuracy [27].

Prospects of phasor measurement technique based on global positioning system (GPS) applied in transient stability control of power system are introduced in Ref. [4]. Using real data collected by phasor measurement unit (PMU), with the aid of GPS and high-speed communication network, online dynamic equivalent of interconnected power grid may be achieved [4].

In this paper, the dynamic equivalence problem is formulated by two objective functions. An evolutionary optimization method based on genetic algorithms is used to solve the problem.

2. Proposition

The main objective of this paper is the external system's model order reduction of an electrical grid, preserving only the frontier nodes. That is, those nodes of the external system directly linked to nodes of the study system. At such frontier nodes, fictitious generators are allocated. The external boundary is defined by the user. Basically, it is composed by a set of buses, which connect the external areas to the study system. There is not restriction about this set. Different operating conditions are taken into account.

2.1. Network reduction

A first condition for an equivalence strategy is the steady state preservation on the reduced grid; this means basically a precise

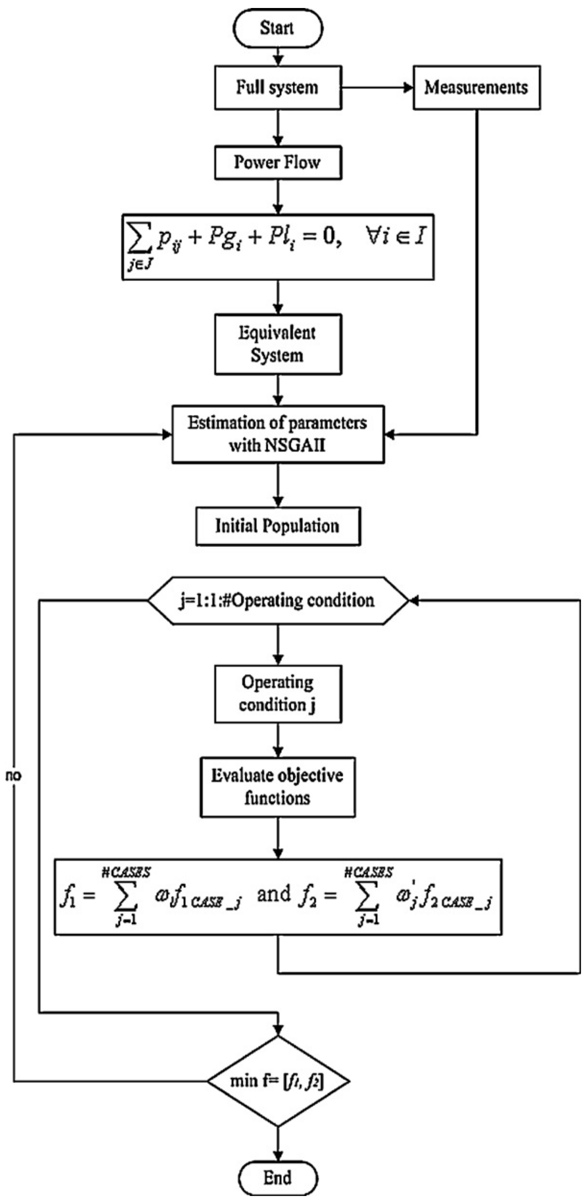

Fig. 2. Proposed strategy's flowchart.

voltage calculation. In this paper, all nodes of the external system are eliminated, except the frontier nodes. By a load flow study, the complex power that should inject some fictitious generators at such nodes can be calculated. The nodal balance equation yields,

$$\sum_{j \in J} p_{ij} + Pg_i + Pl_i = 0, \quad \forall i \in I \tag{1}$$

where I is the set of frontier nodes; J is the set of nodes linked directly to the ith frontier node; p_{ij} is the active power flowing from the ith to jth node; Pg_i is the generation at the ith node; Pl_i is the load at the ith node. Thus, the voltages for the reduced model become equal to those of the full one.

For studies where unbalanced conditions are important, a similar procedure could be followed for the negative and zero equivalent sequences calculation.

2.2. Studied system

The power system shown in Fig. 1 depicts a reduced version of the Mexican interconnected power system. It encompasses 7 regional systems, with a generation capacity of 54 GW in 2004 and an annual consumption level of 183.3 TWh in 2005. The transmission grid comprises a large 400/230 kV system stretching from the southern border with Central America to its northern interconnections with the US. The grids at the north and south of the country are long and sparsely interconnected transmission paths. The major load centers are concentrated on large metropolitan areas, mainly Mexico City in the central system, Guadalajara City in the western system, and Monterrey City in the northeastern system.

The subsystem on the right of the dotted line is considered as the system under study. Thus, the subsystem on the left is the external one. There are five frontier nodes (86, 140, 142, 148 and 188) and six frontier lines (86–184, 140–141, 142–143, 148–143(2) and 188–187). Thus, the equivalent electrical grid has five fictitious generators at nodes 86, 140, 142, 148 and 188. Transient stability models are employed for generators, equipped with a static excitation system; its formulation is described as follows,

$$\frac{d\delta}{dt} = \omega - \omega_0 \tag{2}$$

$$\frac{d\omega}{dt} = \frac{1}{T_j}\left[Tm - Te - D(\omega - \omega_0)\right] \tag{3}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}\left[-E'_g - (x_d - x'_d)i_d + E_{fd}\right] \tag{4}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{d0}}\left[-E'_d + (x_q - x'_q)i_q\right] \tag{5}$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}\left[-E_{fd} + K_A(V_{ref} + V_s - |V_t|)\right] \tag{6}$$

where δ (rad) and ω (rad/s) represent the rotor angular position and angular velocity; E'_d (pu) and E'_q (pu) are the internal transient voltages of the synchronous generator; E_{fd} (pu) is the excitation voltage; i_d (pu) and i_q (pu) are the d- and q-axis currents; T'_{d0} (s) and T'_{q0} (s) are the d- and q-open-circuit transient time constants; x'_d (pu) and x'_q (pu) are the d- and q-transient reactances; Tm (pu) and Te (pu) are the mechanical and electromagnetic nominal torque; Tj is the moment of inertia; D is the damping factor; K_A and T_A (s) are the system excitation gain and time constant; $V_{\rm ref}$ is the voltage reference; V_t is the terminal voltage; V_s is the PSS's output (if installed). The corresponding parameters are selected as typical [28].

2.3. Formulation

Given some steady state operating point (*#CASES*) the following objective functions are defined,

$$\min f = [f_1 f_2]$$

$$f_1 = \sum_{\rm op=1}^{\rm \#CASES} w1_{\rm op} \sum_{k=1}^{\rm Ng\_int} \left[\omega_{k\_{\rm ori}}(t) - \omega_{k\_{\rm equiv}}(x,t)\right]^2 \tag{7}$$

$$f_2 = \sum_{\rm op=1}^{\rm \#CASES} w2_{\rm op} \sum_{k=1}^{\rm Ng\_int} \left[Pe_{k\_{\rm ori}}(t) - Pe_{k\_{\rm equiv}}(x,t)\right]^2 \tag{8}$$

subject to:

$$0 = \sum_{j=1}^{\rm Ngen\_eq} H_j - \sum_{\substack{i=1 \\ i \in L}}^{n} H_i \tag{9}$$

where $\omega_{k\text{-ori}}$ is the time behavior of the angular velocity of those generators in the original system, that will be preserved (Ng_int),

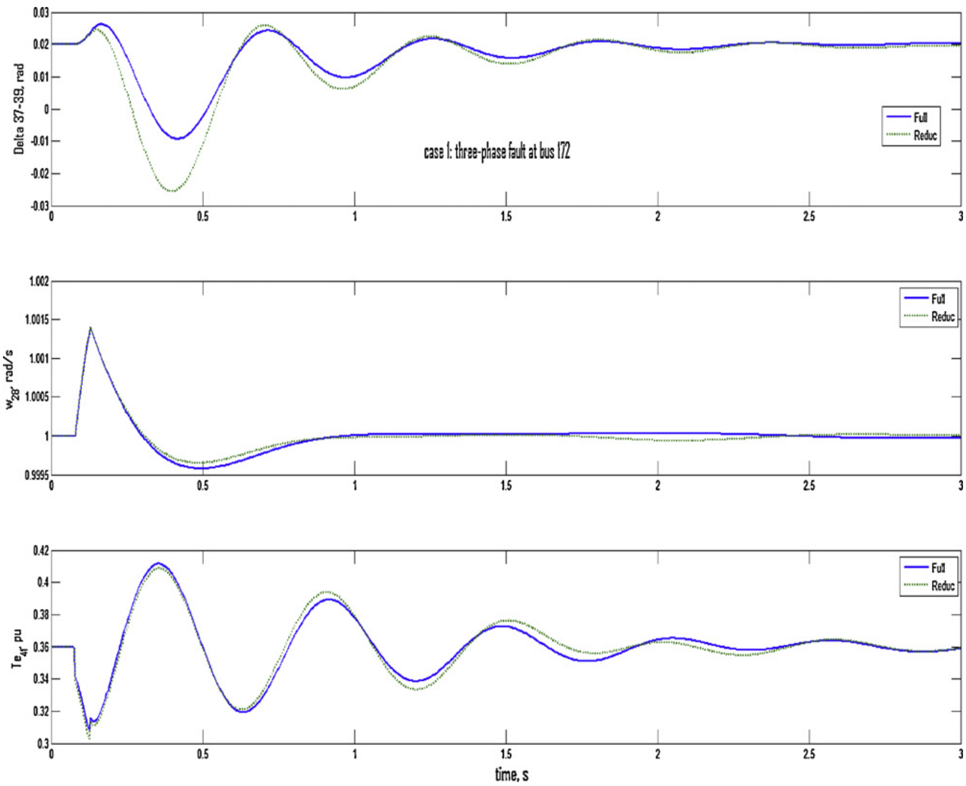

Fig. 3. Fitness assignment of NSGA-II in the two-objective space.

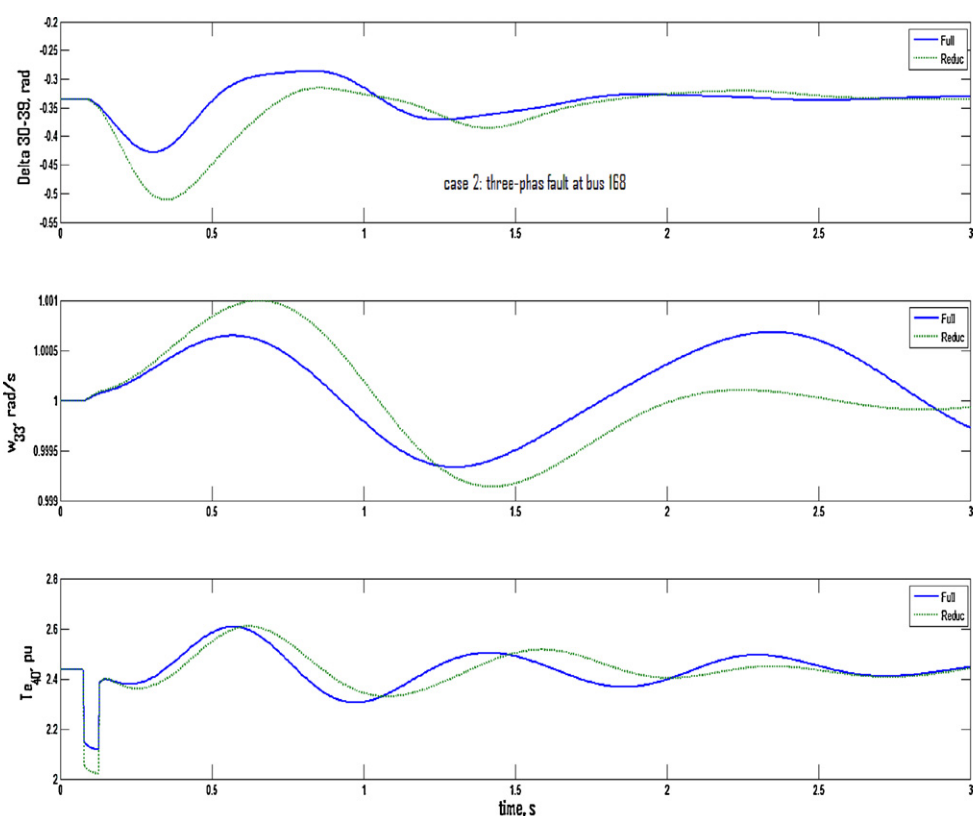

Fig. 4. Case 1: from top to bottom (i) angular position 37 (referred to slack); (ii) angular speed 28; (iii) electrical torque 41, after a three-phase fault at bus 172.

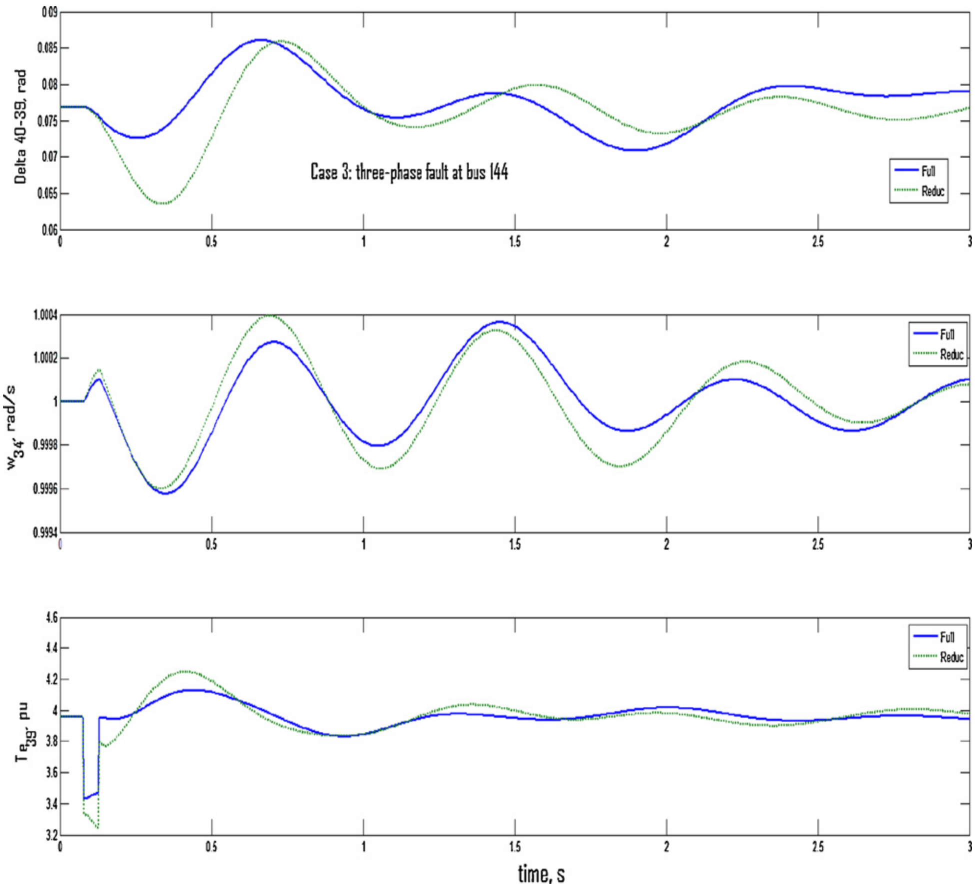

Fig. 5. Case 3: from top to bottom (i) angular position 40 (referred to slack); (ii) angular speed 34; (iii) electrical torque 39, after a three-phase fault at bus 144.

after a disturbance within the internal area; $\omega_{k\text{-equiv}}$ is the time behavior of the angular velocity of those generators in the equivalent system, after the same disturbance within the internal area; $Pe_{k\text{-ori}}$ is the time behavior of the electrical power of those generators of the original system within the internal area; $Pe_{k\text{-equiv}}$ is the time behavior of the electrical power of those generators in the equivalent system within the internal area; H_k is the kth generator's inertia; L is the set of generators that belong to the external system; Ngen_eq is the number of equivalent generators [16,25]. The set of voltages $S = \{V_i, V_j, \ldots, V_k \mid$ complex voltages stemming from PMUs$\}$ has been included in the solution.

The main challenge in a multi-objective optimization environment is to minimize the distance of the generated solutions to the Pareto set and to maximize the diversity of the developed Pareto set. A good Pareto set may be obtained by appropriate guiding of the search process through careful design of reproduction operators and fitness assignment strategies. To obtain diversification special care has to be taken in the selection process. Special care is also to be taken to prevent non-dominated solutions from being lost. Elitism addresses the problem of losing good solutions during the optimization process. In this paper, the NSGA-II algorithm (Non dominated Sorting Genetic Algorithm-II) [29–31] is used to solve the formulation. The algorithm NSGA-II has demonstrated to exhibit a well performance; it is reliable and easy to handle. It uses elitism and a crowded comparison operator that keeps diversity without specifying any additional parameters. Pragmatically, it is also an efficient algorithm that has shown better results to solve optimization problems with multi-objective functions in a series of benchmark problems [31,32]. There are some other methods that may be used. For instance, it is possible to use at least two population-based non-Pareto evolutionary algorithms (EA) and two Pareto-based EAs: the Vector Evaluated Genetic Algorithm (VEGA) [36], an EA incorporating weighted-sum aggregation [33], the Niched Pareto Genetic Algorithm [34,35], and the Nondominated Sorting Genetic Algorithm (NSGA) [29–31]; all but VEGA use fitness sharing to maintain a population distributed along the Pareto-optimal front.

3. Results

In this case, the decision variables, **x**, are eight parameters per each equivalent generator: $\{x_d, x'_d, x_q, x'_q, T'_{d0}, T'_{q0}, H, D\}$. In this paper, for five equivalent generators, there are 40 parameters to be estimated.

Likewise, in this case, a random change in the load of all buses gives rise to the transient behavior. A normal distribution with zero mean is utilized to generate the increment (decrement) in all buses. The variation is limited to a maximum of 50%. The disturbance lasts for 0.12 s and then it is eliminated; the studied time is 2.0 s. To attain more precise equivalence for severe operating conditions, this improvement could require load variations greater than 50%. However, this bound was used in all cases. Fig. 2 depicts a flowchart of the followed strategy to calculate an optimal solution.

In this paper, three operating points are taken into account: (i) Case 1, the nominal case [37]; (ii) Case 2, an increment of 40% in load and generation; (iii) Case 3, a decrement of 30% in load and generation. To account for each operating condition into the objective functions, the same weighted factors have been utilized ($w_i = 1/3$), Eqs. (7)–(8).

Table 1 summarizes the estimated parameters for five equivalent generators, according to the two objective functions. The

Table 1
Parameters of the equivalent under a maximum of 50% in load variation.

	$G_{equiv-1}$		$G_{equiv-2}$		$G_{equiv-3}$		$G_{equiv-4}$		$G_{equiv-5}$	
	f_1	f_2	f_1	f_2	f_1	f_2	f_1	f_2	f_1	f_2
x_d	0.108	0.104	2.140	2.100	1.920	1.910	0.159	0.179	0.324	0.362
x'_d	0.113	0.113	0.819	0.869	0.396	0.396	0.0876	0.132	1.900	1.950
T'_{d0}	10.70	10.70	39.60	39.60	18.80	18.70	11.50	11.50	11.70	11.70
x_q	0.710	0.750	0.530	0.519	0.288	0.308	2.470	2.460	0.705	0.803
x'_q	0.395	0.385	0.874	0.805	0.901	0.926	0.922	0.953	0.882	0.884
T'_{q0}	4.950	4.820	33.30	33.40	4.280	4.100	16.90	16.90	12.80	12.90
H	4.610	4.610	22.27	22.27	47.26	47.26	69.23	69.23	33.93	33.93
D	18.03	18.40	535.6	536.6	239.2	239.1	41.90	42.00	705.1	705.2

electromechanical modes associated to generators of the internal system are closely preserved. These generators are fictitious and basically are useful to preserve some of the main interarea modes between the internal area and the external one [16].

Thus, in order to avoid the identification of the equivalent generators' parameters based on a specific disturbance, in this paper the use of random changes in all the load buses is used. This will give rise to parameters valid for different fault locations. The allowed change in the load (in this paper, 50%) will result in a slight variation of transient reactances. Further studies are required to assess sensitivities. Fig. 3 shows a typical Pareto front for this application. The NSGA-II runs on a Matlab platform and the convergence lasts for 3.25 h for a population of 200 individuals and 20 generations.

It is assumed that phasor measurement units (PMUs) are installed at specific buses (188, 140, 142, 148, and 86 in the external system, and 141, 143, 145, and 182 in the internal system), which basically correspond to the frontier nodes. Likewise, it is assumed that the precise voltages are known in these buses every time. By the inclusion of the PMUs, there is a noticeable improvement in the voltages' information at the buses near them, due to the fact that it is assumed the PMUs' high precision.

In this paper, the simulation results obtained by the full and the reduced system are compared by a closeness measure, the mean squared error (MSE). The goal of a signal fidelity measure is to compare two signals by providing a quantitative score that describes the degree of similarity/ fidelity or, conversely, the level of error/distortion between them. Usually, it is assumed that one of the signals is a pristine original, while the other is distorted or contaminated by errors [38].

Suppose that $\mathbf{z} = \{z_i | i = 1, 2, \ldots, N\}$ and $\mathbf{y} = \{y_i | i = 1, 2, \ldots, N\}$ are two finite-length, discrete signals, where N is the number of signal samples and z_i and y_i are the values of the ith samples in $\mathbf{z}$ and $\mathbf{y}$, respectively. The MSE is defined by,

$$\text{MSE}(z, y) = \frac{1}{N}\sum_{i=1}^{N}(z_i - y_i)^2 \tag{10}$$

Figs. 4–5 illustrate the transient behavior of some representative signals after a three-phase fault at buses 172 (Fig. 4) for the Case 1; and 144 (Fig. 5) for the Case 3. Bus 39 is selected as the slack bus. Values in Table 2 show the corresponding MSE values for the twelve generators of the internal system for each operating case. Such values indicate a close relationship between the full and reduced signals' behavior. In order to improve the equivalence of a specific operating point, it is possible to weight it differently through the factors w_{1-3}, Eqs. (7)–(8). Table 2 shows the MSE's values when Case 2 has a higher weighting than Case 1 and Case 3 ($w_2 = 2/3$, $w_1 = w_3 = 1/6$). These values indicate that a closer agreement is attained between signals with the full and the reduced model. It is emphasized that the equivalence's improvement could require load variations greater than 50% for off-nominal operating conditions.

4. Conclusions

Undoubtedly, the power system equivalents' calculation remains a useful strategy to handle the large amount of data, calculations, information and time, which represent the transient stability studies of modern power grids. The proposed approach is founded on a multi-objective formulation, solved by a genetic algorithm, where the objective functions weight independently each operating condition taken into account. The use of information stemming from PMUs helps to improve the estimated equivalent generators' parameters. Results indicate that the strategy is able to closely preserve the oscillating modes associated to the internal system's generators, under different operating conditions. That is due to the preservation of the machines' inertia. The use of an index to measure the proximity between the signal's behavior after a three-phase fault, indicates that good agreement is attained. In this paper, the same weighting factors have been used to assess different operating conditions into the objective functions. However, depending on requirements, these factors can be modified. The equivalence based on an optimal formulation assures

Table 2
MSE for Case 2 (Three-Phase Fault at Bus 168).

	Angular position		Angular speed		Electrical power	
	$w_k = 1/3$	$w_2 = 2/3$, $w_1 = w_3 = 1/6$	$w_k = 1/3$	$w_2 = 2/3$, $w_1 = w_3 = 1/6$	$w_k = 1/3$	$w_2 = 2/3$, $w_1 = w_3 = 1/6$
Gen 39	2.13E−01	1.54E−01	6.36E−05	6.90E−05	9.40E−02	6.91E−02
Gen 28	1.79E−01	9.39E−02	3.43E−05	2.75E−05	4.09E−05	2.50E−05
Gen 29	1.12E−01	4.96E−02	4.84E−05	2.29E−05	9.25E−04	5.38E−04
Gen 30	1.01E−01	4.27E−02	3.31E−05	1.62E−05	9.75E−04	4.52E−04
Gen 32	2.80E−01	1.02E−01	4.34E−05	2.69E−05	4.26E−04	5.16E−04
Gen 33	2.97E−01	1.09E−01	4.81E−05	3.29E−05	9.85E−04	1.15E−04
Gen 34	1.70E−01	1.04E−01	4.03E−05	4.09E−05	9.19E−03	6.17E−03
Gen 37	1.68E−01	1.08E−01	5.23E−05	5.39E−05	1.12E−02	8.48E−03
Gen 38	1.53E−01	9.54E−02	4.47E−05	4.60E−05	1.29E−02	1.01E−02
Gen 40	1.91E−01	1.15E−01	5.27E−05	5.14E−05	2.26E−03	1.06E−03
Gen 41	1.93E−01	1.18E−01	5.52E−05	5.39E−05	2.50E−04	1.16E−04
Gen 42	1.68E−01	1.07E−01	4.17E−05	4.28E−05	5.23E−05	3.02E−05

proximity between the full and the reduced models. Closer proximity is reached if more stringent convergence's parameters are defined, as well as additional objective functions, as line's power flows, are included.

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