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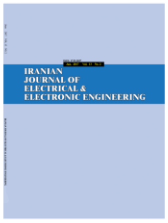
Research Paper



Small-Signal Stability Constrained Model for Generation Development Program Considering Wide-Area Stabilizer

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Abstract: The main idea of this paper is proposing a model to develop generation units considering power system stability enhancement. The proposed model consists of two parts. In the first part, the indexes of generation expansion planning are ensured. Also, small-signal stability indexes are processed in the second part of the model. Stability necessities of power network are supplied by applying a set of robustness and performance criteria of damping. Two parts of the model are formulated as two-objective function optimization that is solved by adaptive non-dominated sorting genetic method-III (ANSGM-III). For better decision-making of the final solution of generation units, a set of Pareto-points have been extracted by ANSGM-III. To select an optimal solution among Pareto-set, an analytical hierarchy style is employed. Two objective functions are compared and suitable weights are allocated. Numerical studies are carried out on two test systems, 68-bus and 118-bus power network. The values of generation expansion planning cost and system stability index have been studied in different cases and three different scenarios. Studies show that, for example, in the 68-bus system for the case of system load growth of 5%, the cost of generation expansion planning for the proposed model increased by 7.7% compared to the previous method due to stability modes consideration and the small-signal stability index has been improved by 6.7%. The proposed model is survived with the presence of a wide-area stabilizer (WAS) for damping of oscillations. The effect of WAS latency on expansion programs is evaluated with different amounts of delay times.

Keywords: Planning, Stability, Wide-Area Damping, Generation.

Nomenclature

ANSGM-III	Adaptive non-dominated sorting genetic method-III
WAS	Wide area stabilizer
PMU	Phasor measurement unit
GEP	Generation expansion planning
TEP	Transmission expansion planning
LOLP	Loss of load probability
SSS	Small-signal stability
AHS	Analytical hierarchy style
SLD	Single line diagram
SSSEI	Small-signal stability expansion index
H_{PGEP}^{IE}	Investment cost of new production units
τ	Inflation rate
v	Lifetime of expansion schedule in year
$IPPU_u$	Initial cost of production unit *u*-th
TC_u	General capacity of production power
$H_{PGEP,O\&M}^{PE}$	Maintenance cost
$H_{PGEP,FC}^{PE}$	Fuel cost
$H_{PGEP,EC}^{PE}$	Emission cost
OP_u	Maintenance cost of *u*-th generation unit
FP_u	Fuel cost of *u*-th generation unit
EP_u	Emission cost of *u*-th generation unit
A_{CL}	Closed-loop power system matrix
E	Weight coefficient related to each index
$\xi_{\min}(A_{CL})$	Minimum damping ratio
Ω_M	Maximum real part among all eigenvalues
Ω_z	Real of *z*-th eigenvalues
$Y(A_{CL})$	Inverse of the largest singular amount

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SV	Singular value of matrix
ss	Sample size
sf	Sampling frequency
ci	Control-limit
pv	Population vector
r_a	Random number
T_A	Regulator time constant
K_A	Regulator gain
D	Machine damping coefficient
M	Inertia coefficient
E'_Q	Generator internal voltage
E_{FD}	Field voltage
I_D	d-axis armature current
I_Q	q-axis armature current

1 Introduction

1.1 Objectives and Approach

STABILITY of power system network is one of the important issues that power system designers and planners are involved with it. Different methods are used to improve the stability performance of power system. In immediate and short term planning, power system stabilizers with various structures are utilized. To improve the single-input stabilizers, multi-input stabilizers with more capabilities are employed [1, 2]. Phasor measurement unit (PMU) implementation with transmission instruments of wide-area signals can create a good opportunity to overcome inter-area modes problems [3]. WAS is a suitable method in damping of low-frequency oscillations. The stability of the power system is largely dependent on the inherent structure of the power system. Power network structure, type of production units, admittance matrix of the power network, and other inherent parameters of the network are important criteria that impact on network stability long-term [4].

Generally, power network over the years is grown by implementing development programs. Generation, transmission, and reactive power expansion planning are three important issues that determine the inherent characteristics of the power system [5, 6]. In this paper, a model for generation expansion planning is presented to ensure the small-signal stability of the power system. Generation expansion planning is a complex procedure that the main aim of it is verifying the locations and technologies for generation investment [7, 8]. Depending on the management policies of the power network, generation expansion planning (GEP) is investigated along with a wide range of objectives from cost-minimizing in monopoly systems to profit maximization in deregulated structure [9]. Generation expansion planning is traditionally based on a minimum-cost development plan for the existing power network over a planning horizon. The objective function of these plans is identified as the sum of the investment cost for newly added units, fixed operation and maintenance cost, and variable operational cost for newly added units. So far, a simultaneous study on GEP and small-signal stability had not been addressed. GEP without stability study can lead to an unstable and un-robust system in the future that any small disturbances can unstable power system. In the future, a weak power system needs more stabilizers with more costs to deal with different disturbances existing in the power system. Current power systems are experiencing various types of disturbances. Renewable generation units with intermittent nature of power production are one of the problems that current power systems are involved with it. Delay time in wide-area stabilizer is one of the important problems in power systems that employ wide-area signals to damp small-signal oscillations.

1.2 Literature Review

Generation expansion planning has been studied in numerous references. In [10], a general study on the coordination of generation, transmission, and energy storage expansion planning has been presented. Generation units, energy storage systems, and demand response programs are considered as flexible tools that reliability and flexibility of the power system are ensured by them. The proposed planning program is formulated as a mixed-integer non-linear problem that is linearized by Taylor’s series. The reliability of the system is tested by using load uncertainty, intermittent nature of wind power. Simultaneous coordination of GEP and transmission expansion planning (TEP) with short-circuit constraints has been proposed in [11]. The Short-circuit level of the power system is survived in a system with wind units. Hybrid generation and transmission expansion planning are aimed to decrease the short-circuit level of the power system.

In [12], two important uncertainties have been involved in generation expansion planning, load forecast, and the price of new equipment. The simulation results confirm that units retirement consideration reduce the cost of compensation of old generation units. GEP based on loss of load probability has been discussed in [9]. A dynamic GEP model with loss of load probability (LOLP) as a reliability index has been proposed. Investment, operation, and maintenance costs are three targets used in the objective function. In the proposed model, generation expansion planning is done with lower costs that ensure the reliability of the power system. Small-signal stability analysis of the power system has been addressed in different references. The small-signal effect of virtual generation synchronous has been analyzed in [13]. Virtual synchronous generators are a new type of converter control scheme for wind units that it is considered as conventional units. To test the small-signal stability effect of virtual generators, model tools are used. The results confirm that virtual generators can decrease the small-signal stability performance of the power system. Formulation of delayed cyber-physical system has been done in [14]. The model proposed in this reference is based on Hessenberg form that it preserves the inherent sparsity in the general state matrix. Also, this model increases efficiency in the stability and control procedures. In [4], a dynamic model for transmission expansion planning is proposed. In this method, transmission part of system is developed considering the enhancement of small-signal stability. A probabilistic-based method is used to specify the optimal control policy that it increases the performance of small-signal stability of power system. In [15], a new approach has been verified to long-term planning of wind units considering voltage stability limitations. The main objectives of this model are maximizing the profits of wind unit inventor and minimizing the generation costs. Based on modal analysis, the best location for wind unit has been funded.

1.3 Contributions

In this paper, a comprehensive model has been presented to combine generation expansion planning and small-signal stability of power systems. Small-signal stability of a power system mainly depends on the inherent properties of the power system and power network layout. Inherent specifications and network structure are determined by the planning process. In generation expansion planning, production formation of a power system is defined. The type, location, and capacity of generation units can affect on the stability of the system. To have a robust system with a suitable damping ratio, generation planning should be coupled with stability analysis. A complete study has been presented in this paper to discuss the GEP role in the oscillation damping of the power system. Two objective representation is verified based on the cost of generation planning and small-signal stability indexes. The cost of generation planning consists of two parts, investment cost, and operation cost. Maintenance, fuel, and emission cost are three indicators that operation cost is formed based on them. The second objective function in the multi-objective model is based on small-signal stability criteria. The equations of the power system are linearized according to the network layout of an *n*-machine power system. Eigenvalues are extracted based on the state matrix of the system and stability index is presented considering minimum damping ratio, maximum real part, the inverse of the largest singular value, and condition number. The multi-objective problem is solved by ANSGM-III that it has a good stability in the extraction of Pareto-points. The best solution should be selected among Pareto-optimal points. The selection process is done by the AHS method and bidirectional comparison.

The main contributions of this paper can be summarized as follows:

- The combined model of generation expansion planning considering small-signal stability performance of the power system is presented.
- The multi-objective representative of the problem is considered and that is solved with ANSGM-III.
- The role of WAS and delay of wide-area signals in GEP is evaluated with multiple scenarios.

To evaluate the proposed method, two test systems, 118-bus and 68-bus are employed. Three scenarios and four cases are carried out on two test systems. Wide area damping controller has a high potential in damping of low-frequency swings. This controller by employing wide-area signals as input of stabilizer can play an effective role in planning of generation development and system stability. In scenario 3, it is assumed that system generators are equipped with WAS. GEP cost and stability index are compared in scenario 3 with other scenarios. Time delay is an important problem that wide area controller is involved with it. Planning cost and small-signal stability have been compared for different time delays.

2 The Proposed Planning Method

Generation expansion planning considering the small-signal stability issue consists of two basic parts. A set of generation expansion planning indexes have been determined in the first part of the proposed model. In the second part of the proposed model, the small-signal stability (SSS) performance of the power system is evaluated by the weighted sum of stability criterion. Coordinated GEP and small-signal stability improvement have been formulated as the following equation:

$$GEP^{SSSE} = \min\{GEPI, SSSEI\} \tag{1}$$

Usually, the principal purpose of GEP is minimizing some objective functions with ensuring some restrictions. The system planner is willing to develop the power system in the best stability situation by minimizing the small-signal stability expansion index (SSSEI) as a small-signal stability indicator.

2.1 Formulation of Part of Generation Expansion Planning

GEPI is a mathematical multi-objective problem that consists of several objectives and limitations. The *GEPI* aims to create a balance between productions and demand that includes two objectives: investment and performance cost. *GEPI* can be verified as follows [16]:

$$GEPI = \eta_1 H_{PGEP}^{IE} + \eta_2 H_{PGEP}^{PE} \tag{2}$$

The investment cost of new production units, H_{PGEP}^{IE}, can be addressed as follows:

$$H_{PGEP}^{IE} = \frac{\tau(\tau+1)^{\nu}}{(\tau+1)^{\nu}-1}\sum_{u} IPPU_u TC_u \tag{3}$$

where τ and v are inflation rate and lifetime of expansion schedule in year. $IPPU_u$ and TC_u are initial cost of production unit u-th and general capacity of production power that it can be added to the system. The performance cost of generation expansion planning consists of three parts, maintenance cost, fuel cost, and emission cost that it can be formulated as follows:

$$H_{PGEP}^{PE} = H_{PGEP,O\&M}^{PE} + H_{PGEP,FC}^{PE} + H_{PGEP,EC}^{PE} \tag{4}$$

where $H_{PGEP,O\&M}^{PE}$, $H_{PGEP,FC}^{PE}$, and $H_{PGEP,EC}^{PE}$ indicate maintenance, fuel and emission cost of generation expansion planning process and can be given by the following equations:

$$H_{PGEP,O\&M}^{PE} = \sum_u OP_u TC_u \tag{5}$$

$$H_{PGEP,FC}^{PE} = \sum_u FP_u TC_u \tag{6}$$

$$H_{PGEP,EC}^{PE} = \sum_u EP_u TC_u \tag{7}$$

where OP_u, FP_u, and EP_u are maintenance, fuel, and emission cost of u-th generation unit.

2.2 Formulation of Part of SSS Enhancement

The linearized model of the n-machine power system can be given as follows [17]:

$$\begin{cases} \Delta\dot{\delta} = \omega_s \Delta\omega \\ \Delta\dot{\omega} = M^{-1}\left(-\Gamma_{Epq}^{TE}\Delta \mathrm{E}'_Q - \Gamma_{Id}^{TE}\Delta I_D - \Gamma_{Iq}^{TE}\Delta I_Q - D\Delta\omega\right) \\ \Delta\dot{E}'_Q = T'_{DO}\left(-\Gamma_{Epq}^{Eq}\Delta \mathrm{E}'_Q - \Gamma_{Id}^{Eq}\Delta I_D + \Delta E_{FD}\right) \\ \Delta\dot{E}'_{FD} = (-\Delta E_{FD} - K_A(\Gamma_{Epq}^{VT}\Delta \mathrm{E}'_Q + \Gamma_{Id}^{VT}\Delta I_D + \Gamma_{Iq}^{VT}\Delta I_Q \\ \qquad + \Delta U_{PSS}))T_A^{-1} \end{cases} \tag{8}$$

where

$$\begin{cases} \Delta I_D = \Gamma_{\delta}^{Id}\Delta\delta + \Gamma_{Epq}^{Id}\Delta E'_Q \\ \Delta I_Q = \Gamma_{\delta}^{Iq}\Delta\delta + \Gamma_{Epq}^{Iq}\Delta E'_Q \end{cases} \tag{9}$$

I_D and I_Q are d-and q-axis armature current, E'_Q and E_{FD} are generator internal and field voltage and D and M are machine damping and inertia coefficient. T_A and K_A are regulator time constant and gain. Γ is the coefficient value of each variable after linearization.

Based on the above equations, for a linearized system, we have:

$$\begin{cases} \dot{x}_e(t) = A_e x_e(t) + B_e u_e(t) \\ y_e(t) = C_e x_e(t) + D_e u_e(t) \end{cases} \tag{10}$$

where $x_e = [\delta \quad \omega \quad E'_Q \quad E_{FD}]^T$ and $u_e = [U_{PSS}]^T$.

If we define the linear damping controller as follows:

$$\begin{cases} \dot{x}_d(t) = A_d x_d(t) + B_d u_d(t) \\ y_d(t) = C_d x_d(t) + D_d u_d(t) \end{cases} \tag{11}$$

The closed-loop power system matrix is verified as bellows [18]:

$$A_{CL} = \begin{bmatrix} A_e & B_e C_d \\ 0 & A_d \end{bmatrix} \tag{12}$$

$SSSEI$ related to A_{CL} matrix can be verified as follows:

$$SSSEI = -E_1\left(\frac{\xi_{\min}(A_{CL})}{\bar{\xi}_{\min}(A_{CL})}\right) + E_2\left(\frac{\Omega_M(A_{CL})}{\bar{\Omega}_M(A_{CL})}\right) + E_3\left(\frac{\sum_{z=1}^{N}\Omega_z^2(A_{CL})}{\sum_{z=1}^{N}\bar{\Omega}_z^2(A_{CL})}\right) - E_4\left(\frac{\Upsilon(A_{CL})}{\bar{\Upsilon}(A_{CL})}\right) + E_5\left(\frac{\ell(A_{CL})}{\bar{\ell}(A_{CL})}\right) \tag{13}$$

where E_1 to E_5 are weight coefficient related to each index, $\xi_{\min}(A_{CL})$ is the minimum damping ratio for A_{CL}, Ω_M is the maximum real part among all eigenvalues, Ω_z is the real of z-th eigenvalues, $\Upsilon(A_{CL})$ is the inverse of the largest singular amount, $\ell(A_{CL})$ is the singular value of A_{CL} matrix. $\ell(A_{CL})$ is defined as $\ell(A_{CL}) = SV_{\max}(A_{CL})/SV_{\min}(A_{CL})$. $SV_{\max}(A_{CL})$ and $SV_{\min}(A_{CL})$ are the maximum and minimum singular value.

3 The Flowchart of Problem Solution

Multi-objective optimization is a branch of multi-criteria decision making that focuses on problems that optimize more than one objective function simultaneously. In a multi-objective optimization problem, there is no single solution that simultaneously optimizes each objective. In this situation, it is defined that the objective functions are in conflict with each other and there are several Pareto optimal solutions. A solution point is identified as non-dominated Pareto optimal if none of the objective functions can be improved in value without degrading other objective values. ANSGM-III is a modified version of the multi-objective genetic algorithm that is employed in this paper to solve the multi-objective problem presented in (1).

ANSGM-III is a reference-point based multi-objective NSGA-II algorithm that is more efficient to solve problems with more than two objectives. ANSGM-III is able to successfully find a well-converged and well-diversified set of points. In higher-dimensional problems, multi-objective algorithms face an increasingly difficult task of maintaining diversity in the Pareto-optimal front. The supply of a set of reference points and ANSGM-III niching technique in finding a Pareto-optimal solution has caused diversity preservation of solutions. Also, ANSGM-III procedure does not require any additional parameters. It has been demonstrated that ANSGM-III can work with a small number of user-supplied structured or randomly assigned reference points, thereby making the method suitable for a many-objective preference-based optimization-cum-decision-making approach. It has been shown that ANSGM-III can be used to find only a few points with a small population size, thereby reducing the computational efforts. ANSGM-III performance has been found to be much better than a classical generating method in many-objective problems.

The proposed planning method is done based on three steps. In the first step, the presented model is solved by employing adaptive ANSGM-III [19, 20]. We consider *ss*, *sf*, and *ci* as sample size, sampling frequency, and control-limit, and the population vector is defined as *pv* = (*ss*, *sf*, *ci*). With these assumption *pv* is verified as follows:

$$\begin{cases} ss_i = [ss_{\min} + rand.(ss_{\max} - ss_{\min})] \\ sf_i = [sf_{\min} + rand.(sf_{\max} - sf_{\min})] \\ ci_i = [ci_{\min} + rand.(ci_{\max} - ci_{\min})] \end{cases} \qquad (14)$$

Crossover and mutation procedure is done based on the following equation:

$$\begin{cases} of_i = r_a pv_i + (1 - r_a) pv_r \\ of_r = (1 - r_a) pv_i + r_a pv_r \end{cases} \qquad (15)$$

where r_a is a random number between [0,1].

Adaptive normalization is done for each objective $F_j(pv_i)$, $j = 1, 2, \ldots, m$ according to following equations:

$$F_j^N = \frac{F_j(pv_i) - \varphi_j^*}{\varphi_j^t - \varphi_j^*} \qquad (16)$$

where

$$\varphi_j^* = \min F_j(pv_i) \qquad (17)$$

φ^*_j is calculated by applying the following relation:

$$\begin{pmatrix} \varphi_1^t - \varphi_1^* \\ \varphi_2^t - \varphi_2^* \\ \vdots \\ \varphi_m^t - \varphi_m^* \end{pmatrix} = \begin{pmatrix} \beta_1^{\max} - \varphi_1^* \\ \beta_2^{\max} - \varphi_2^* \\ \vdots \\ \beta_m^{\max} - \varphi_m^* \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \qquad (18)$$

where $\beta_j^{\max}$ is as:

$$\beta_j^{\max} = F_j(pv^*) - \varphi_j^* \qquad (19)$$

$$pv^* = \arg\min AB(pv_i, \omega) \qquad (20)$$

$$AB(pv_i, \omega) = \max\left[\frac{F_j(pv_i) - \varphi_j^*}{\omega_{ij}}\right]$$

$$i \neq j, \;\; \omega_{ij} = 0, \;\; \text{else} \;\; \omega_{ij} = 1 \qquad (21)$$

In the next step, reference points are produced. Members with the closest Euclidean distance are considered as the reference point.

In the final step for ANSGM-III, niche-preserving is done to correct the fitness function according to the convergence index. To produce the next generation, particle with better convergence is used.

After generation of Pareto-set by ANSGM-III, selection of an optimal solution among Pareto-points is done by AHS (analytical hierarchy style) [21]. Bidirectional comparison forms the basis of the AHS technique. Objective functions of the proposed model are compared pairwise to construct comparison matrix. Based on the geometric mean method the best optimal solution is found. The flowchart of the proposed algorithm is shown in Fig. 1.

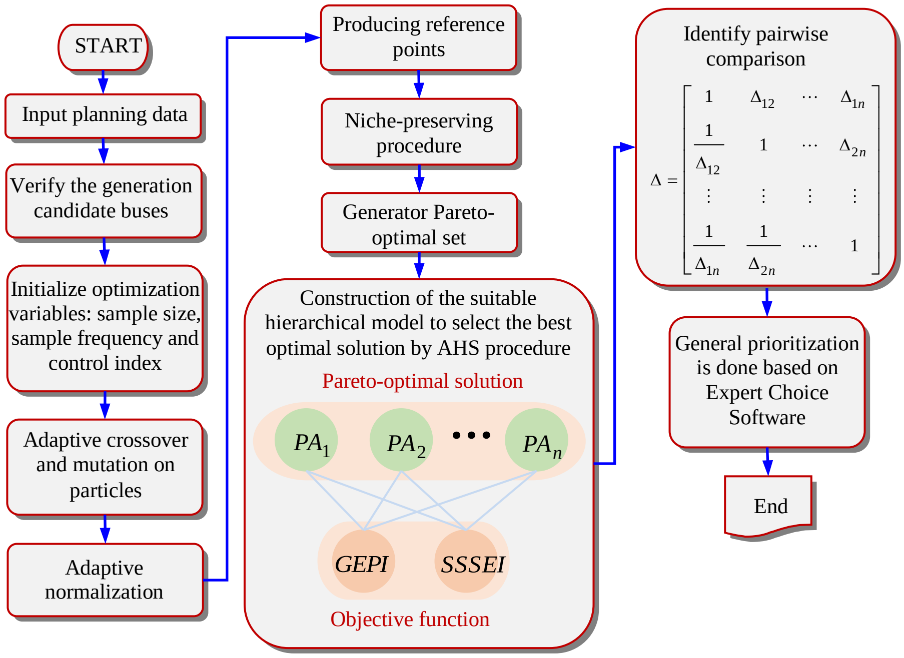


Fig. 1 The flowchart of problem.

4 Numerical Study

A numerical test has been performed in this section to evaluate the proposed model. The proposed approach is tested on the IEEE 118-bus and 68-bus test system that single line diagram (SLD) of those has been depicted in Figs. 2 and 3.

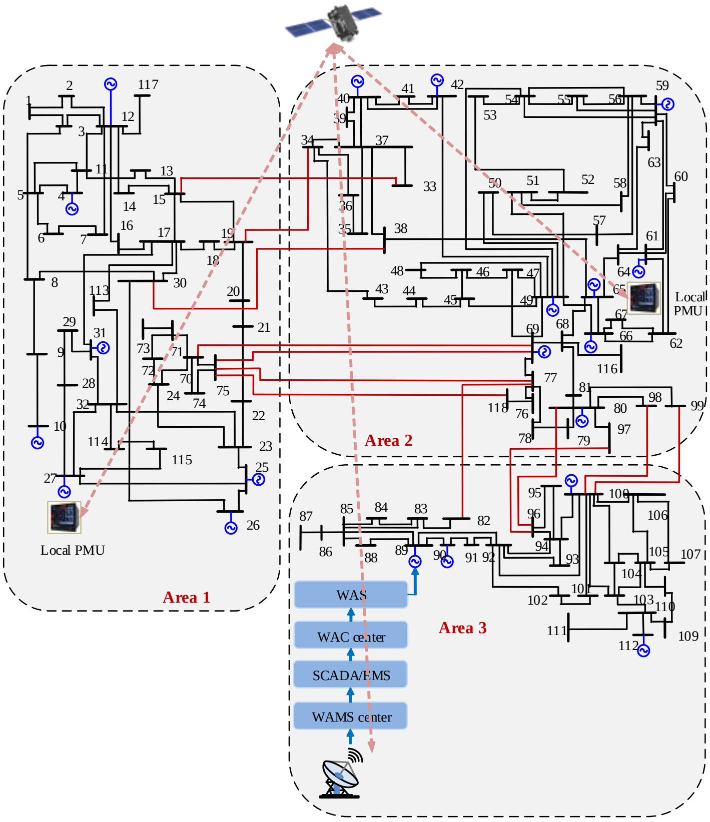


Fig. 2 SLD of 118-bus test system.

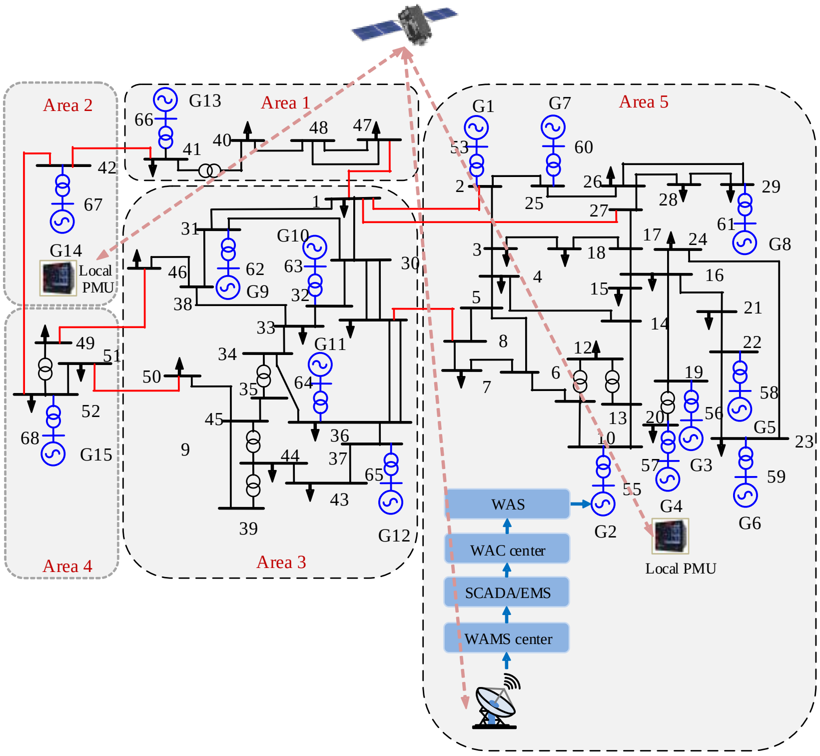


Fig. 3 SLD of 68-bus test system.

The candidate generation data have been given in Tables 1 and 2 [22, 23].

To evaluate the proposed model, three scenarios have been considered as follows:

- Scenario 1 (S1): In this scenario, it is assumed that generation expansion planning is done without considering small-signal stability criteria. In other words, the *GEPI* is considered alone.
- Scenario 2 (S2): In this scenario, the generation expansion planning is done based on the proposed model according to *GEPI* and *SSSEI*.
- Scenario 3 (S3): In this scenario, the proposed model is used based on *GEPI* and SSSEI considering the wide-area stabilizers. The structure of wide-area stabilizer with wide-area signals has been shown in Fig. 4 [24, 25].

To find the best input for wide-area stabilizer, the singular value decomposition method is used [26]. To select the wide-area signal for the input of WAS, a geometric technique has been utilized. Four different cases have been assumed to discuss the proposed model:

- Case 1(C1): With annual peak load increase of 5%.

Table 1 The candidate generation units for 118-bus test system.

	Bus No.	Generating capacity [MW]	Investment cost [M$]	Operation cost [$/MWh]
U_1	1	90	135	18
U_2	4	50	56	21
U_3	4	70	90	20
U_4	4	40	45	20
U_5	6	100	124	20
U_6	10	180	207	18
U_7	14	100	124	20
U_8	14	90	135	18
U_9	18	150	163	19
U_{10}	20	50	56	20
U_{11}	20	50	56	20
U_{12}	20	60	62	18
U_{13}	21	130	152	19
U_{14}	22	200	223	17
U_{15}	27	80	101	18
U_{16}	38	110	138	19
U_{17}	39	200	226	18
U_{18}	50	90	133	20
U_{19}	51	150	172	19
U_{20}	62	110	116	19
U_{21}	75	110	166	20
U_{22}	80	170	185	19
U_{23}	88	200	223	17
U_{24}	93	100	124	20
U_{25}	94	200	223	17
U_{26}	96	140	178	19
U_{27}	101	170	203	18
U_{28}	114	190	215	18
U_{29}	116	110	126	19
U_{30}	118	90	115	20

Table 2 The candidate generation units for 68-bus test system

	Bus No.	Generating capacity [MW]	Investment cost [M$]	Operation cost [$/MWh]
U_1	67	128	140	14
U_2	49	196	215	21.5
U_3	35	148	162	16.2
U_4	33	171	188	18.8
U_5	9	119	130	13
U_6	47	115	126	12.6
U_7	3	174	191	19.1
U_8	5	63	69	6.9
U_9	36	70	77	7.7
U_{10}	7	77	84	8.4
U_{11}	56	109	119	11.9
U_{12}	76	175	192	19.2
U_{13}	50	171	188	18.8
U_{14}	11	60	66	6.6
U_{15}	45	110	121	12.1

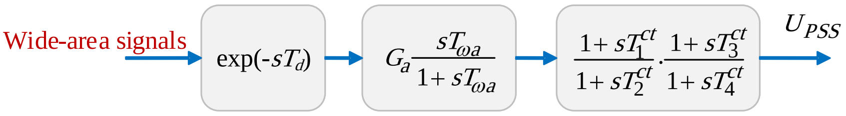
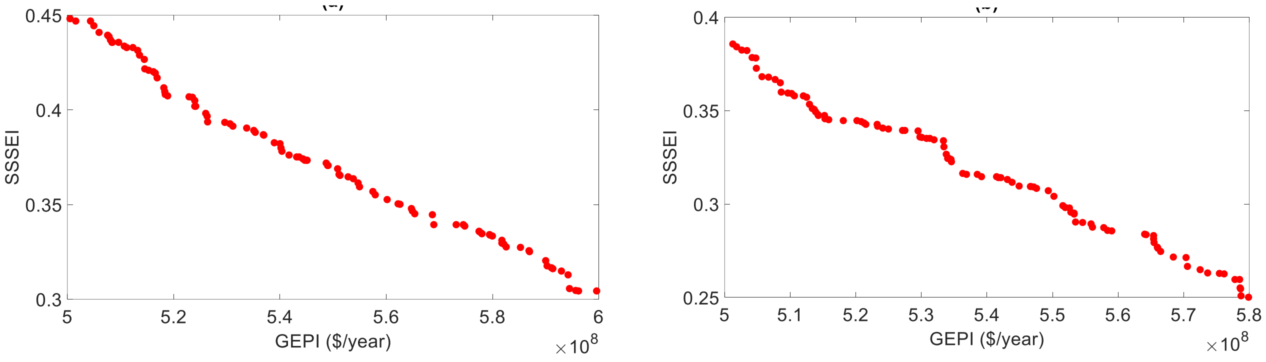
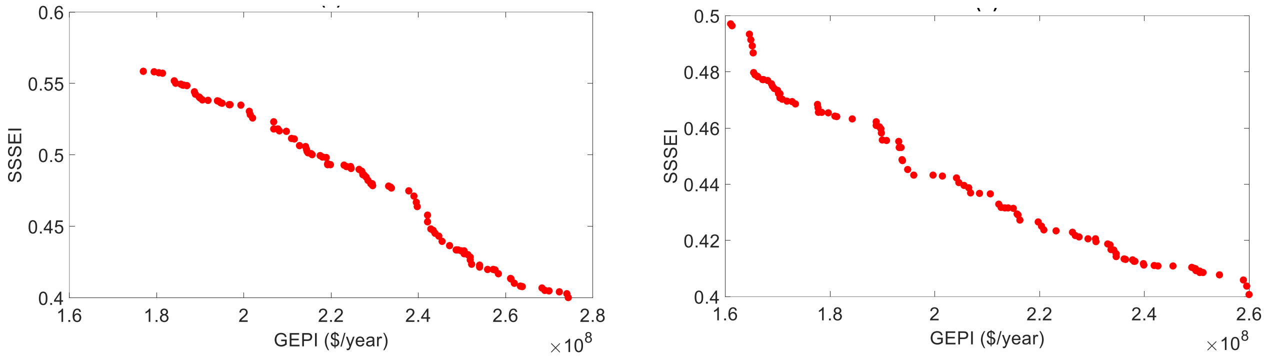


Fig. 4 The structure of WAS.



(a) (b)

Fig. 5 Pareto-optimal archive for a) scenario 2 and b) scenario 3 for 118-bus test system.



(a) (b)

Fig. 6 Pareto-optimal archive for a) scenario 2 and b) scenario 3 for 68-bus test system.

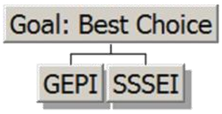


Fig. 7 Hierarchy view of problem.

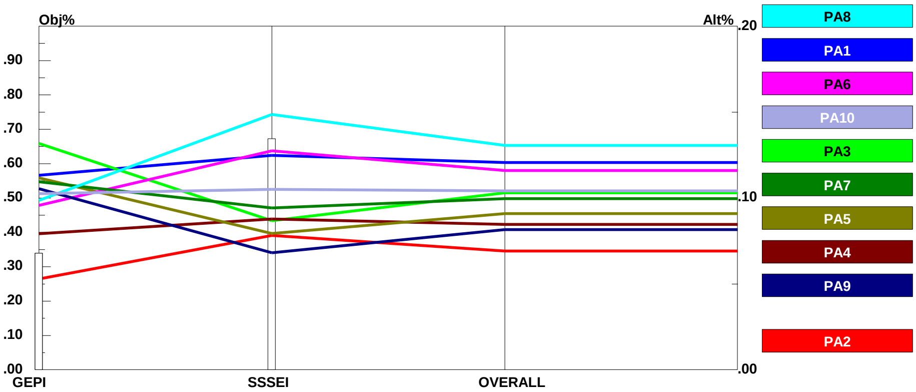


Fig. 8 Efficiency sensitivity curve.

- Case 2(C2): With annual peak load increase of 10%.
- Case 3(C3): With annual peak load increase of 15%.
- Case 4(C4): With annual peak load increase of 20%.

ANSGM-III is employed to solve the multi-objective optimization of the proposed model. Pareto-set for two scenarios 2 and 3 in 118-bus and 68-bus test system has been depicted in Figs. 5 and 6.

Expert choice software is implemented to find the best solution among Pareto-set. The hierarchy view of the problem has been depicted in Fig. 7.

Efficiency sensitivity curve for ten Pareto-point and two objective functions, *GEPI* and *SSSEI* have been given in Fig. 8 for 118-bus test system.

Fig. 9 shows the alternatives priorities with respect to two objectives, GEPI and SSSEI at a time.

The behaviors of ten Pareto-points based on two objective functions have been shown in Figs. 10 and 11.

Also, general prioritization weighting has been

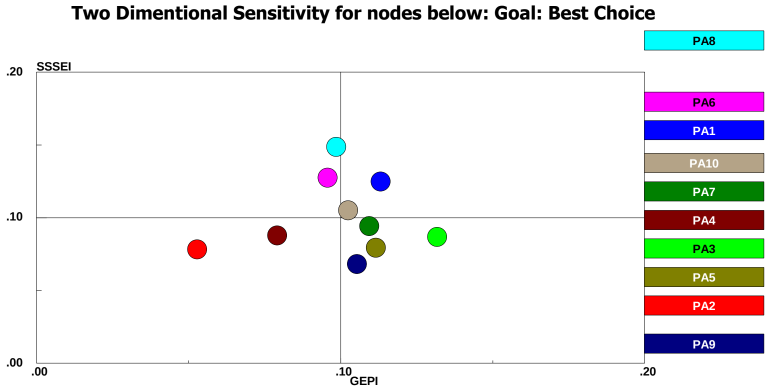


Fig. 9 Priorities in two-dimensional plot.

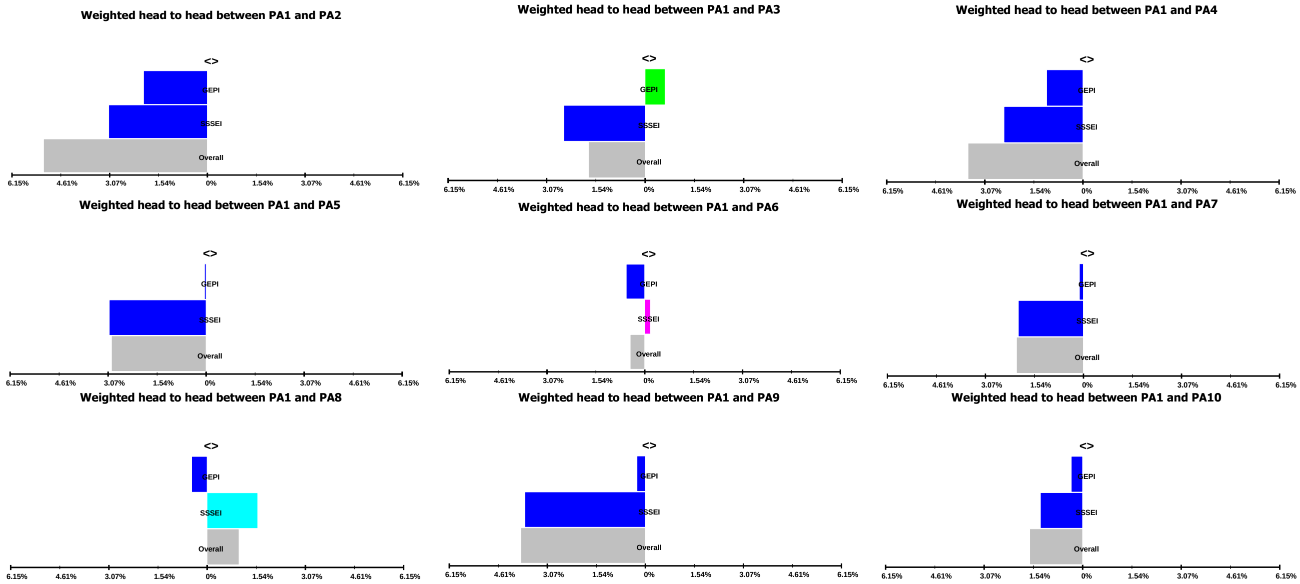


Fig. 10 Prioritization of the Pareto-points with respect to GEPI and SSSEI.

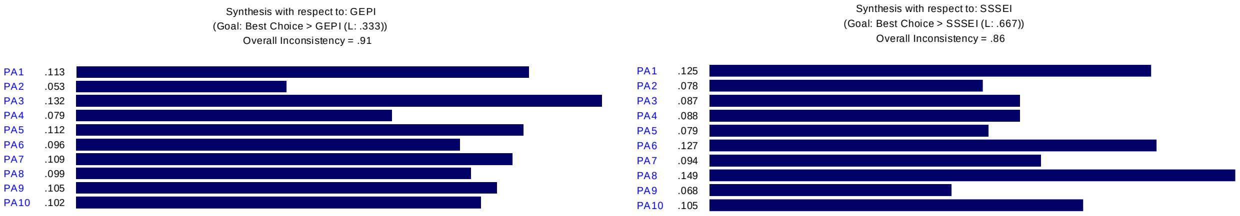


Fig. 11 Prioritization weight of each point and objective function.

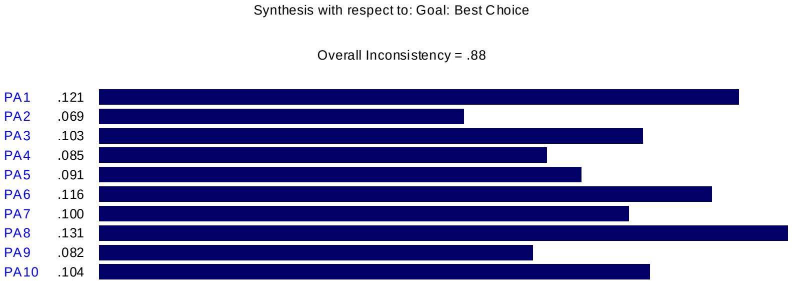


Fig. 12 General prioritization.

depicted in Fig. 12. Based on Fig. 12, PA_8 is the best solution among points.

The new generation units added to systems for three scenarios and four cases have been given in Tables 3 and 4.

Table 3 The new units added to system I.

	Scenario 1				Scenario 2				Scenario 3			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
U_{1}	1	1	0	0	1	1	0	0	0	0	0	1
U_{4}	1	1	1	0	0	1	0	0	0	0	1	0
U_{4}	0	0	0	0	1	1	0	1	0	0	1	0
U_{4}	0	0	1	0	0	0	0	0	0	0	1	0
U_{6}	0	1	0	1	1	1	1	1	1	0	0	1
U_{10}	1	0	0	1	0	1	1	0	1	1	0	0
U_{14}	0	1	0	1	0	0	1	1	0	0	1	0
U_{14}	0	0	1	0	0	1	1	1	0	1	1	1
U_{18}	0	0	0	1	0	1	1	0	0	1	1	0
U_{20}	1	0	0	1	0	0	1	0	0	0	0	1
U_{20}	0	0	0	0	1	1	1	1	1	1	1	0
U_{20}	0	1	1	1	0	1	0	0	0	1	1	1
U_{21}	0	0	0	0	0	0	1	0	0	0	0	0
U_{22}	0	1	1	1	0	0	1	0	0	1	0	0
U_{27}	1	0	1	0	1	1	0	1	1	1	0	0
U_{38}	0	0	1	0	0	0	0	0	0	1	0	1
U_{39}	1	1	0	1	1	1	1	1	1	1	0	0
U_{50}	0	0	0	0	0	1	0	0	0	1	1	1
U_{51}	1	0	0	0	0	0	0	1	0	0	0	0
U_{62}	0	0	1	0	0	0	0	1	0	0	0	1
U_{75}	1	1	0	1	0	0	0	1	1	0	1	0
U_{80}	1	0	1	1	0	1	1	0	0	0	0	1
U_{88}	0	1	1	0	1	0	0	1	1	1	1	1
U_{93}	0	0	1	0	0	0	0	1	0	0	1	1
U_{94}	1	1	0	0	1	0	0	0	0	0	0	1
U_{96}	0	0	0	1	1	0	1	0	1	0	1	0
U_{101}	0	1	0	0	1	0	0	1	1	0	0	1
U_{114}	0	0	1	0	0	0	0	1	0	0	0	0
U_{116}	1	0	0	1	1	1	1	1	1	0	1	0
U_{118}	0	0	1	0	1	1	0	0	1	1	1	1

Table 4 The new units added to system II.

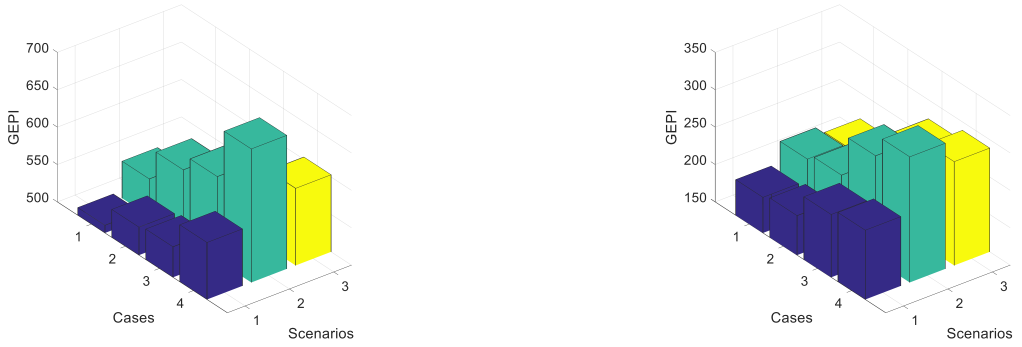
	Scenario 1				Scenario 2				Scenario 3			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
U_{67}	1	1	0	1	1	0	1	1	0	0	1	1
U_{49}	1	0	0	0	0	1	1	0	1	0	1	1
U_{35}	0	0	1	0	0	0	1	0	0	0	1	0
U_{33}	0	0	0	1	0	0	0	1	1	1	0	0
U_{9}	0	1	0	1	0	0	0	1	0	1	0	0
U_{47}	1	0	0	1	0	1	1	1	0	1	0	0
U_{3}	0	0	0	0	1	0	0	0	0	0	0	0
U_{5}	0	0	0	0	1	0	0	1	0	1	0	1
U_{36}	0	1	1	0	1	0	1	0	1	1	1	1
U_{7}	1	1	0	0	0	0	0	0	0	1	0	1
U_{56}	0	0	0	1	1	0	0	1	1	0	0	1
U_{76}	0	1	1	0	1	1	1	0	0	0	1	1
U_{50}	0	0	1	0	0	1	0	1	0	0	0	0
U_{11}	0	0	1	1	0	0	1	1	0	1	0	0
U_{45}	1	1	1	1	0	0	0	1	1	1	1	1

The results of two objective functions, *GEPI* and *SSSEI* in three scenarios and four cases have been given in Figs. 13 and 14. Numerical results show that in the three considered scenarios, as the annual growth rate of the system load increases, the cost index and the stability index increase. By comparing the three different scenarios we conclude that the cost index GEPI, for the second scenario is higher than the first scenario for different cases. For example, in the first system for the first case, the cost in the second scenario has increased by 7.7% than the first scenario. In the third scenario compared to the second scenario, we will have a lower cost because of the use of wide-area controllers. For example, in the first system for the first case, the third scenario has a cost reduction of 3.8% compared to the second scenario. Also, by comparing the stability index, we can conclude that the system is more stable in using the proposed model or in the second scenario. For example, for the first system, in the first case, the stability index in the second scenario has improved by 6.7% compared to the first scenario. Also, the third scenario has a better stability index than the second one. For example, in the second system for the fourth case, the stability index in the third scenario is improved by 7.1% compared to the second scenario.

From all the above discussions, it can be concluded that in the case of multi-objective optimization with two objectives, the cost of generation expansion and small-signal stability, considering the wide-area controller, we will have the best situation. In this case, the development cost has been reduced while the small-signal stability of the system has been ensured. In the case of dual-objective optimization without the use of wide-area damping controller, generation expansion cost compared to the case of single-objective optimization with the aim of generation expansion cost, the development cost has increased due to stability considerations.

4.1 Effect of Time Delay in Expansion Planning

In WAS, remote signal considered as controller input is sent by communication channels that this signal is involved with a time delay, T_d. A small time-delay can lead to instability in the power system. Thus, time delay should be discussed in WAS design and expansion planning proposed in this paper. The value of *GEPI* and *SSSEI* for four amounts of time delay, T_d = 100, 150, 200, and 250 ms have been extracted and it is compared during four states as shown in Figs. 15 and 16. By comparing the figures, we can conclude that by increasing the amount of delay of wide-area signals, the system development planning costs increase. Larger delays also reduce the stability level of the system.

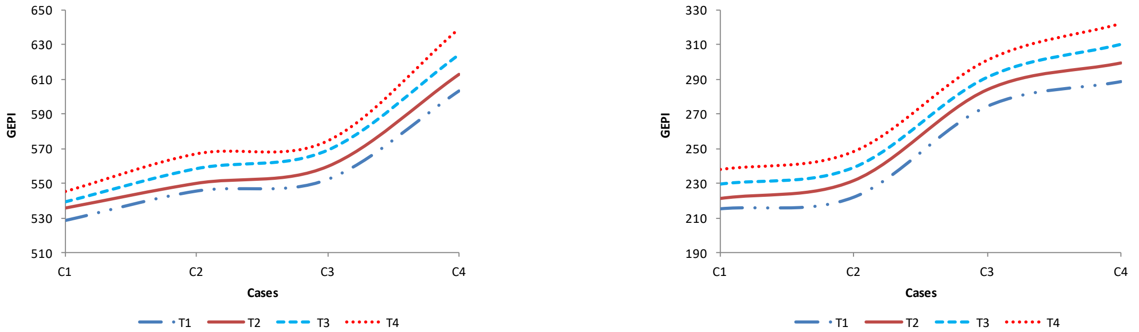


(a) (b)

Fig. 13 Comparison of *GEPI* for a) test system I and b) test system II.

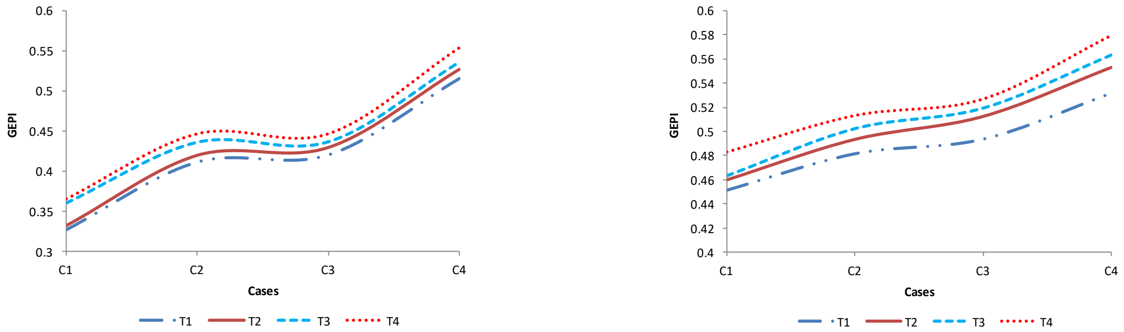
(a) (b)

Fig. 14 Comparison of *SSSEI* for a) test system I and b) test system II.



(a) (b)

Fig. 15 Comparison of *SSSEI* for four different time delays in scenario 3 for (a) system I (b) system II.



(a) (b)

Fig. 16 Comparison of *GEPI* for four different time delays in scenario 3 for (a) system I (b) system II.

5 Conclusions

In this paper, a method has been proposed to involve small-signal stability issue in generation expansion planning. In general, the stability of the power system has been associated with structure and equipment existing in it. The arrangement of the elements, the location of the various components, and distance between buses are the important factors which can affect the stability of the small-signal of the power system. We can achieve a high level of stability by properly planning the equipment. In this work, the problem of generation expansion planning is discussed based on two basic goals: a) to meet the needs of the network and b) providing small-signal stability of the network. A linearized model of *n*-machine power system is developed and the state matrix of it is extracted. Based on the state matrix of the system, the small-signal stability index is considered with weighted sum of minimum damping ratio, maximum real part, inverse of the largest singular value, and maximum and minimum singular value. Generation expansion planning is presented with weighted sum of investment and operation costs. The multi-objective optimization is solved by ANSGM-III and the best solution is found by the AHS method. The obtained results of the proposed approach are analyzed in three different scenarios: a) planning without stability index, b) planning with generation expansion and stability index, and c) the proposed model with wide-area stabilizers. Generation cost in scenario 2 increases than scenario 1 and the stability index improves. In other words, the proposed model will increase the cost of developing the system generation, but on the other side, we will have a stable system. Creating a robust system will prevent future costs of the power grid. Due to the positive effects that wide-area controllers have on power system damping, the use of such controllers improves the small-signal stability index of the system and reduces the cost of generation development. The time delay of WAS has a detrimental effect on the stability performance of the system. In this paper, the proposed model is tested with different time delays and the indices are extracted. Time delay reduces system stability index and increases generation expansion cost.

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