Considering FACTS in Optimal Transmission Expansion Planning

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***Abstract*—The expansion of power transmission systems is an important part of the expansion of power systems that requires enormous investment costs. Since the construction of new transmission lines is very expensive, it is necessary to choose the most efficient expansion plan that ensures system security with a minimal number of new lines. In this paper, the role of Flexible AC Transmission System (FACTS) devices in the effective operation and expansion planning of transmission systems is examined. Effort was taken to implement a method based on sensitivity analysis to select the optimal number and location of FACTS devices, lines and other elements of the transmission system. Using this method, the transmission expansion plan for a 9 and a 39 bus power system was performed with and without the presence of FACTS with the use of DPL environment in Digsilent software 15.1. Results show that the use of these devices reduces the need for new transmission lines and minimizes the investment cost.**

Keywords-transmission; expansion;FACTS;9 bus; 39 bus; DPL

I. INTRODUCTION

In order to provide reliable electrical energy to meet the demand, power grid equipment must have the required capacity and ability and several limiting factors are to be considered [1]. Growth in consumer demand may cause the existing electrical grid to be inadequate and thus further research is needed to determine the time of adding new equipment and the actual pieces of equipment needed. Expansion planning of electric power system is divided into three major parts including generation expansion planning (GEP), transmission expansion planning (TEP) and distribution expansion planning (DEP). TEP must lead to a system that is able to transport power with the necessary quality and reliability and maintain grid constrains in the occurrence of the event [2]. In [3], TEP problem by considering consumption-based carbon emission accounting has been analyzed. In [4], a bi-level solving approach is presented. In [5], an approach based on constructive heuristic algorithms (CHA) to solve nonlinear TEP problems is presented. In [6] a stochastic multi-stage approach is proposed. A review of TEP in deregulated environments can be found in [7]. Authors in [8] suggested a fuzzy multi-objective optimization model that initially breaks down into several single-objective parts. Authors in [9] presented a fuzzy approach. A further investigation on the relationship between the number of states and uncertainty is presented in [10]. Authors in [11] have focused also on the economic aspect of TEP. In this paper, transmission expansion planning in the absence and presence of FACTS devices is simulated by Digsilent software. Backward method is chosen in this paper as an effective approach to determine the optimal number and location of FACTS devices.

II. TRANSMISSION EXPANSION PLANNING-TEP

Generally, the purpose of TEP is to offer an expansion plan for economic power supply in a way that the reliability of the system can be maintained or improved [12]. If the transmission system is not adequately expanded, the competition, which is one of the main characteristics of the power market, is flawed [13]. Many researchers investigated classical and heuristic methods of solving TEP [14-18]. TEP problems is divided to four main sections: 'input data', 'objective function', 'equality and inequality constraints', and 'planning criteria' that are briefly discussed in the following sections.

A. Input Data

The input data includes network topology, characteristics of transmission lines and other transmission equipment, cost of power generation, construction costs for new equipment, estimated production and consumption in the period of planning studies [19, 20]. One of the most important input data for TEP is estimated consumption in the future.

B. The Objective Function

The objective function is a cost function defined by what is important for TEP planners. The aim of the objective function is the definition of the priorities of constructions. Generally, in TEP problems the objective function tries to minimize investment costs.

C. Equal and Inequal Constraints

They include the restrictions and requirements, mainly technological and economical, which should be considered through TEP planning.

D. Planning Criteria

They include concepts such as the desired system voltage, thermal stresses, security, stability and short circuit levels. The common purpose of all these criteria is to guarantee the quality and reliability of the transmitted power in both normal and critical operation conditions. In this paper, thermal and voltage criteria are considered simultaneously.

I. FACTS DEVICES

TEP problem requires extensive costs and studies. Therefore, it is better to try to postpone this by performing effective operation of the existing transmission system. Production and control of reactive power in power systems is closely related to the TEP problem. The usual method for producing reactive power is the installation of serial and parallel capacitors at the demand side. The semiconductor and power electronics industry, proposed the concept of Flexible AC Transmission Systems (FACTS). Using these devices leads to decrease the need for adding new lines and equipment and expands their capability in for short intervals [21]. Applying FACTS devices in power system has many advantages compared to conventional methods of reactive power generation such as fast responding, strict control, and flexible curves. These devices compared to conventional methods have higher installation cost. FACTS devices such as SVC, STATCOM, SSSC and UPFC are used to solve the TEP problem. Several studies have been done on the impact of FACTS devices in TEP. It was shown that studies on how to increase the capacity of the transmission system and prevent excessive develop have been investigated by using the FACTS devices [22]. Problem reports about the transmission systems development in the absence of FACTS is presented in [23]. FACTS equipment were introduced as an efficient tool that makes the TEP more flexible [24].

II. BACKWARD METHOD TO SOLVE TEP

The backward method falls in the category of sensitivity analysis methods and can be implemented in any given power system by a large variety of software regardless of dimensions. Thus, this method has no limitations in its implementation with any analytical software [25] which also means that it is rather faster compared to dynamical methods [25]. In backward method, all possible system elements are assigned an initial value and then by removing one of them at each algorithm's step, the optimal point is obtained. This algorithm is an efficient tool in solving TEP problems. According to this algorithm, at first all the lines are practically added to base power system and so, the primary power system is created. Then, each of these lines should be separately removed one after another from primary power system temporarily. After each removal action the remaining terms of system will be examined in normal operation (NO) and contingency operation (CO) modes (in the event of "N-1" contingency). Each time after evaluation of the remaining system, following conditions should be considered:

- Transmission Lines whose removal from the primary system causes the isolation of any bus, cannot be removed.
- Transmission Lines whose removal from the primary system causes the increase of loading in whether NO or CO, cannot be removed.
- Transmission Lines whose removal from the primary system causes the treat of voltage stability, cannot be removed.

Each of these constrains leads to the impossibility to remove part of the lines in each stage. Among the set of lines whose elimination did not conflict with any issues mentioned above, removal priorities are determined by the objective function. The same procedure will be repeated with each step. By removing each hypothetical line, the objective function corresponding to remaining lines is calculated in each stage. Lines with smaller objective function value have priority to be removed from the primary system. This procedure is repeated among stages until the removal of any line in reduced power system leads to violation of at least one of these three constrains. In this stage, the developed power system is obtained at minimal investment cost which guarantees essential reliability of power system.

III. IMPLEMENTATION OF THE PROPOSED METHOD

In this paper, the backward method used to solve TEP is a semi-dynamic method. It has been implemented on 9-bus and IEEE-39-bus power systems. Implementation of the objective function and constraints is achieved by using loop in loop DPL programming in Digsilent software. Implementing the proposed approach requires close scrutiny of buses voltage value, current flux of lines, etc, in normal operation and critical conditions (n-1). In reviewing the critical operation mode, it is necessary after removing each line to analyze parameters corresponding to the remaining elements. This procedure should be carried out through loop in loop DPL programming so that after removing each line the remaining parameters can be analyzed accurately. Since the 9-bus standard system has a symmetric structure in comparison with other standard systems, the possibility of having equal construction cost for any lines is more than any other systems. In this paper, at first the transmission expansion of 9-bus system is examined, considering the costs of few lines are equal. In this particular case, the priority of construction is with a line or set of lines which balanced the power flow in NO mode. For this purpose, through a series of lines with the same cost at each stage, loading of all remaining lines in NO mode are evaluated. The line or set of lines whose construction leads to smaller amount of standard deviation corresponding to the loading of all lines in the system, and thereby more balanced power flow and reduced depreciation, has the priority and so will be constructed. The objective function and constraints of the proposed method are presented below. It should be noted that in all equations the loss of system is neglected. The objective function (when the line '*t*' is removed):

$$F(x) = \sum_{\substack{r=1 \\ r \neq x}}^{N} C(r).L_r + \alpha.P_{Loss,total}(x) + C_{FACTS,total} \qquad (1)$$

$$0 < \alpha << 1$$

where:

N is the number of all candidates in each step after removing the line x,

C(r) is total cost of investment for candidate r per km,

L_r is length of candidate line r [km],

$P_{loss,\ total}(x)$ is the total real power losses in the power system after elimination the line x [MW] and

$C_{FACTS,\ total}$ is total cost of investment for construction FACTS device in each case.

The α is used when the cost of two or more capable lines for installing are equal. The dimension of it is $/MW. The equations that describe the model have been represented in following.

- Power balance equations

Active power:

NO: $P_{ij} = P_{g_i} - P_{d_i}$ (2)

CO: $P_{ij}^{co} = P_i^{co} - P_{d_i}$ (3)

Reactive power:

NO: $Q_{ij} = Q_{g_i} - Q_{d_i}$ (4)

CO: $Q_{ij}^{co} = Q_i^{co} - Q_{d_i}$ (5)

where:

P_{ij} is active power flow in the line ij from the bus i,

P_{gi} is active power generated at bus i,

P_{di} is active power consumed at bus I,

Q_{ij} is reactive power flow in the line ij from the bus i,

Q_{gi} is reactive power generated at bus i and

Q_{di} is reactive power consumed at bus i.

- Thermal capacity constraints

NO: $\sqrt{\left[P_{ij}\right]^2 + \left[Q_{ij}\right]^2} \le S_{L_n,ij}$ (6)

CO: $\sqrt{\left[P_{ij}^{co}\right]^2 + \left[Q_{ij}^{co}\right]^2} \le S_{L_n,ij}$ (7)

where $S_{Ln,ij}$ is the nominal thermal capacity of the existing line between bus i and j.

- Voltage constraints

NO: $V_{L,i}^{\min} \ge 0.95^{pu.}$ (8)

CO: $V_{L,i}^{\max} \le 1.05^{pu.}$ (9)

where $V_{L,i}^{\min}$ and $V_{L,i}^{\max}$ are the minimum and maximum voltage amplitude in both NO and CO mode at the bus i, respectively.

- Frequency stability constraint

$$\exists i : \frac{\partial P_{ij}}{\partial \delta_{ij}} > 0 \ , \delta_{ij} < \frac{\pi}{2} \quad (10)$$

where δ_{ij} is the voltage angle deviation between bus *i* and *j*.

Mentioned procedure is applied once at the absence and another at the presence of FACTS in series and in parallel and the results of these two modes are compared. The planned 6.5 % annual growth in consumption for 20 years in a 9-bus system is divided to two 10-year periods. So that after the first 10 years the growth of production and consumption is 188 % and at the end of 20 years it will be equal to 352 % of the current value. Then this method is applied to the IEEE-39-bus power system in a 16-year period divided into two periods with a 6.5 % annual growth in consumption. In both 9 and 39 power systems, growth in consumption is uneven. Construction of several power plants in several buses is also taken into consideration. Also, the prices shown in the following content of this paper is the today's equivalent of prices with interest rate of 10%. In relation to technical limitations of installing FACTS devices, it should be noted one of the undesirable impacts of FACTS devices on power system is the improper effects on distance relays existing in [26]. Depending on mentioned distance relay, above undesirable effect may cause mistakes in diagnosis of fault location in some of distance relays. It is assumed in this paper that the aforementioned technical limitations force us to implement FACTS devices in particular buses and lines in power system, and not in all of them [27]. It is assumed according to mentioned technical limitation in 9-bus power system, buses 5 and 8, and lines 2-8 are capable of installing FACTS devices. Also in 39-bus power system buses 4, 7, 12, 15 and 27, and lines 5, 7, 15, 25 and 32 are capable of installing FACTS devices. All calculated costs are in USD.

IV. Simulation Results

A. Implementation on 9-Bus Power System

Figure 1 shows the basic system and Figure 2 shows the primary system for the expansion planning. Corrugated lines in Figure 2 indicate the candidate lines for expansion of the power system.

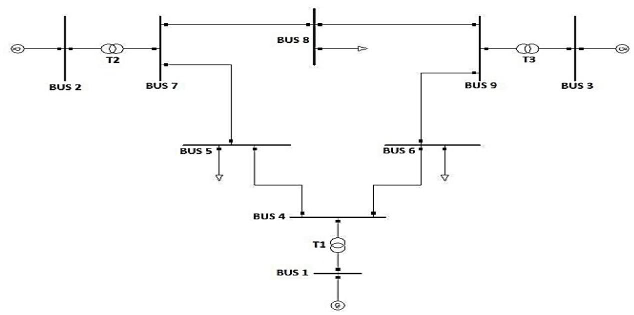

Fig. 1. Basic system 9-bus system

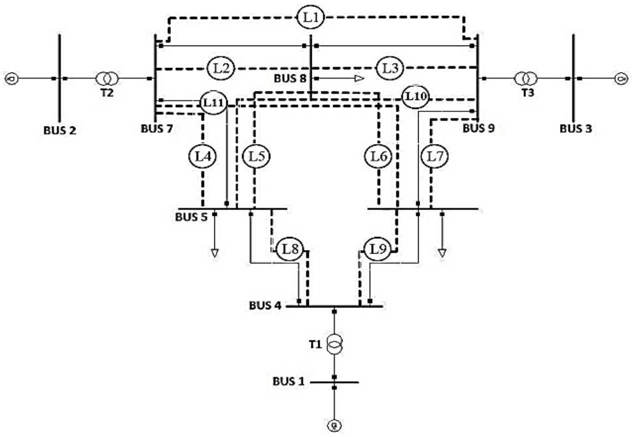

Fig. 2. Primary system for the expansion planning

1) TEP without FACTS devices

a) First expansion plan-no FACTS devices

Voltage violations and expanded transmission system at the end of first expansion plan is shown in Figure 3. In this expansion, a total of 260 km of new 230 kV line is to be constructed. According to the loads and basic power system transformers, a 300 MVA transformer in bus 1 and two 100 MVA transformers in buses 2 and 3 should be added.

b) Second expansion with FACTS devices

In this expansion, a total of 200 km of new 230 kV line is necessary to be constructed According to the loads and basic power system transformers, a 300 MVA transformer in bus 1 and two 200 MVA transformers in buses 2 and 3 should be added.

2) Considering SVC in TEP

Results for optimal locating of SVC using backward method is given in Table I. Expanded transmission system at the end of first expansion plan is shown in Figure 5.

a) First expansion plan considering SVC

The total cost of FACTS devices that have been constructed is 12 million. In this expansion, a total of 180 km of new 230 kV line is necessary to be constructed. According to the loads and basic power system transformers, a 200 MVA transformer in bus 1 and two 100 MVA transformers in buses 2 and 3 should be added.

b) Second expansion plan considering SVC

Expanded transmission system at the end of second expansion plan is shown in Figure 6. In this expansion, a total of 190 km of new 230 kV line is necessary to be constructed . According to the loads and basic power system transformers, a 300 MVA transformer in bus 1 and two 200 MVA transformers in buses 2 and 3 should be added.

3) Considering STATCOM in TEP

Results for optimal locating of STATCOM using backward method is given in Table II.

Voltage violations in stage 10:

Elimination of L6: (full load examine)

Outage of L2 *causes* $V_{BUS\_8} = 0.943^{pu.}$

Elimination of L6: (full load examine)

Outage of L8 *causes* $V_{BUS\_5} = 0.938^{pu.}$

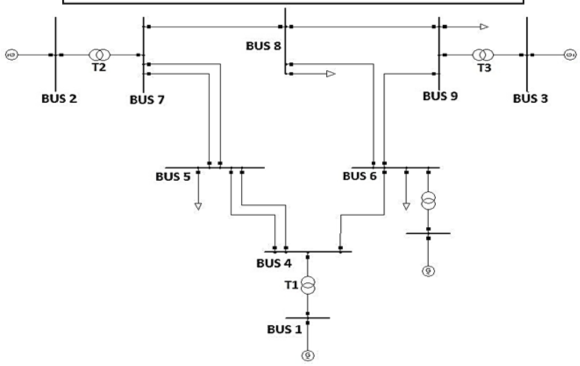

Fig. 3. Expanded transmission system at the end of first expansion plan

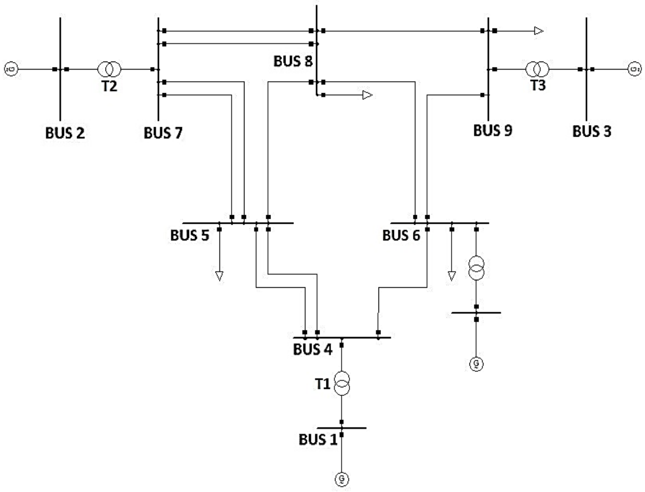

Fig. 4. Expanded transmission system at the end of second expansion plan

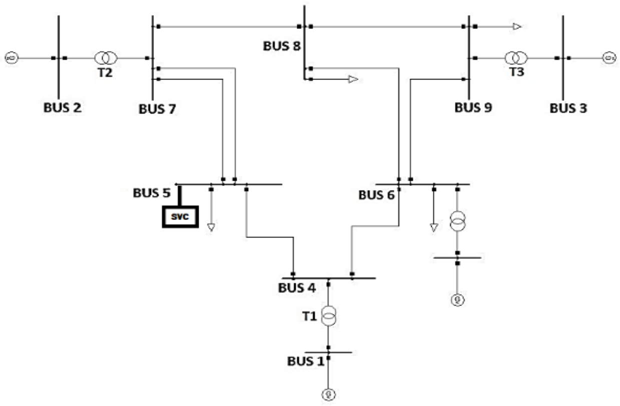

Fig. 5. Expanded transmission system at the end of first expansion plan

TABLE I. OPTIMAL LOCATION OF SVC USING BACKWARD METHOD IN 9-BUS POWER SYSTEM.

Location Of SVC	Total Cost Of First Expansion	Total Cost Of Second Expansion	Total Cost
Bus 5	187	72	259
Bus 8	272	72	344

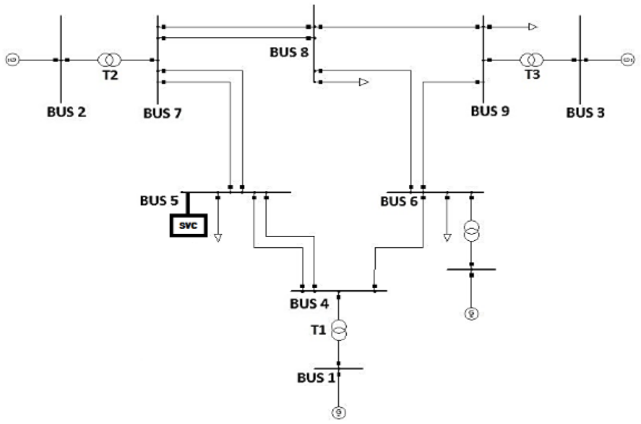

Fig. 6. Expanded transmission system at the end of second expansion plan

TABLE II. OPTIMAL LOCATION OF STATCOM USING BACKWARD METHOD IN 9-BUS POWER SYSTEM

Location Of STATCOM	Total Cost Of First Expansion	Total Cost Of Second Expansion	Total Cost
Bus 5	194	71	265
Bus 8	279	71	350

a) First expansion plan considering STATCOM

Expanded transmission system at the end of first expansion plan is shown in Figure 7. The total cost of FACTS devices to be constructed is 20 million. In this expansion, a total of 180 km of new 230 kV line was necessary to construct .According to the loads and basic power system transformers, three 100 MVA transformer in buses 1, 2 and 3 should be added.

a) Second expansion plan considering STATCOM

Expanded transmission system at the end of second expansion plan is shown in Figure 8. In this expansion, a total of 190 km of new 230 kV line is necessary to be constructed. According to the loads and basic power system transformers, just two 200 MVA transformer in buses 2 and 3 should be added and first transformer not to need for extending.

4) Considering SSSC in TEP

Results for optimal locating of SSSC using backward method is given in Table III.

a) First expansion plan considering SSSC

Expanded transmission system at the end of first expansion plan is shown in Figure 9. The total cost of FACTS been constructed is 30 million. In this expansion, a total of 180 km of new 230 kV line is necessary to be constructed. According to the loads and basic power system transformers, a 400 MVA transformer in bus 1 and two 100 MVA transformers in buses 2 and 3 should be added.

b) Second expansion plan considering SSSC

Expanded transmission system at the end of second expansion plan is shown in Figure 10. In this expansion, a total of 110 km of new 230 kV line is necessary to be constructed . According to the loads and basic power system transformers, a 400 MVA transformer in bus 1 and two 200 MVA transformers in buses 2 and 3 should be added.

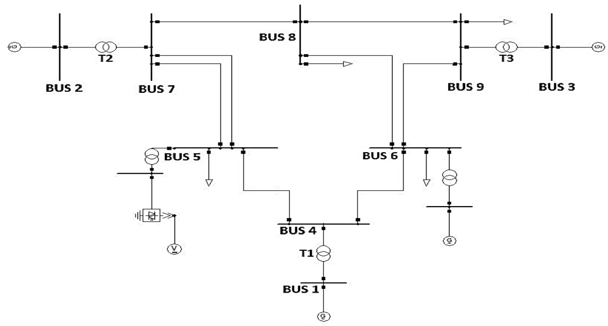

Fig. 7. Expanded transmission system at the end of first expansion plan

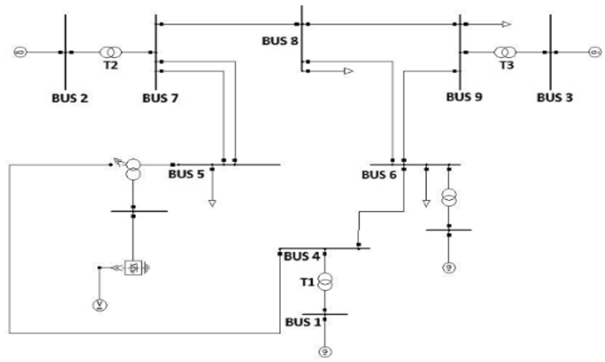

Fig. 8. Expanded transmission system at the end of second expansion plan

TABLE III. OPTIMAL LOCATION OF SSSC USING BACKWARD METHOD IN 9-BUS POWER SYSTEM

Location Of SSSC	Total Cost Of First Expansion	Total Cost Of Second Expansion	Total Cost
L2	311.5	73	384.5
L3	340	43.5	383.5
L4	292.5	43.5	336
L5	292.5	43.5	336
L6	292.5	43.5	336
L8	207	43.5	250.5

5) Considering UPFC in TEP

Results for optimal locating of UPFC using backward method is given in Table IV. Optimal location of UPFC was acquired by using backward method in the 9-bus power system.

a) First expansion plan considering UPFC

Expanded transmission system at the end of first expansion plan is shown in Figure 11. The total cost of FACTS been constructed is 40 million. In this expansion, a total of 180 km of new 230 kV line was necessary to construct. According to the loads and basic power system transformers, a 400 MVA transformer in bus 1 and two 100 MVA transformers in buses 2 and 3 should be added.

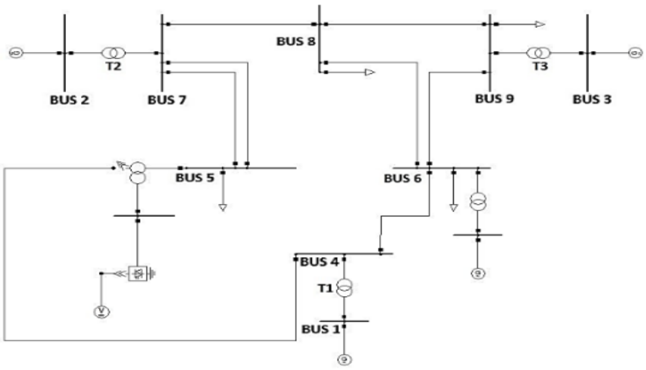

Fig. 9. Expanded transmission system at the end of second expansion plan

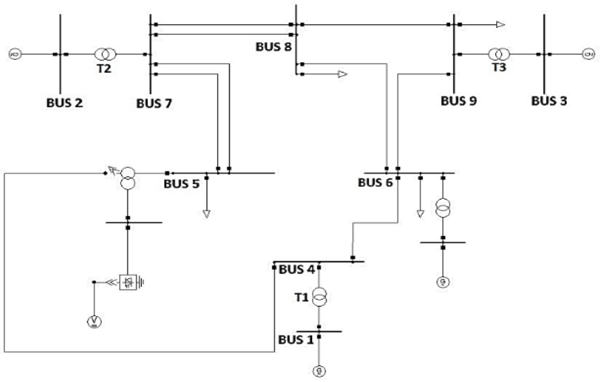

Fig. 10. Expanded transmission system at the end of second expansion plan

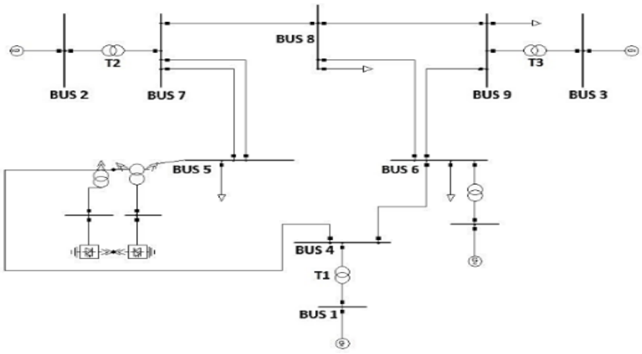

Fig. 11. Expanded transmission system at the end of first expansion plan

b) Second expansion plan considering UPFC

Expanded transmission system at the end of second expansion plan is shown in Figure 12. In this expansion, a total of 110 km of new 230 kV line is necessary to construct. According to the loads and basic power system transformers, a 400 MVA transformer in bus 1 and two 200 MVA transformers in buses 2 and 3 should be added. Overview of lines that should be constructed in various states of expansion is shown in Table V. According to the results presented in Table V, the devices include the series portion having a greater impact in reducing the need for construction of new lines on the power system. The occurrence indicated above reasons that it is possible to control the real and reactive power flow in the line containing a series of FACTS in order to effectively reach the desired size and angle of voltage. However, about devices that only include a parallel section, bus voltage measurements controlled until the injection of reactive power must be within the limits of their capacity otherwise they are unable to keep the voltage above the set value. Following overview of power system total losses in different states of expansion is given in Table VI. According to Table VI, by considering FACTS devices in transmission system expansion planning, losses in expanded system are not decreased and in some cases, are increased. The current equivalent to the total cost of system expansion in each of the scenarios shown in Figure 13.

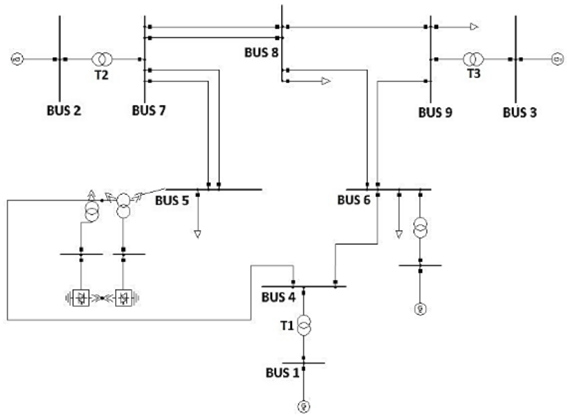

Fig. 12. Expanded transmission system at the end of second expansion plan

TABLE IV. OPTIMAL LOCATION OF UPDFC USING BACKWARD METHOD

Location Of UPFC		Total Cost Of First Expansion	Total Cost Of Second Expansion	Total Cost
Parallel Portion	Series portion			
BUS 5	L4	302.5	47.5	350
	L5	302.5	47.5	350
	L8	217	43.5	260.5
BUS 8	L2	321.5	77	398.5
	L3	350	47.5	397.5
	L5	302.5	47.5	350

TABLE V. LINES THAT SHOULD BE CONSTRUCTED IN VARIOUS STATES OF EXPANSION

TEP	First Expansion	Second Expansion
Lack Of FACTS	L4 – L6 – L8	L2 – L5
Considering SVC	L4 – L6	L2 – L8
Considering STATCOM	L4 – L6	L2 – L8
Considering SSSC	L4 – L6	L2
Considering UPFC	L4 – L6	L2

TABLE VI. TOTAL REAL AND REACTIVE POWER LOSSES IN THE POWER SYSTEM IN THE VARIOUS STATES OF EXPANSION

TEP	First Expansion		Second Expansion	
	Reactive Losses (MVAR)	Active Losses (MW)	Reactive Losses (MVAR)	Active Losses (MW)
No FACTS	402.27	16.55	279.31	44.12
SVC	102.9	16.58	271.84	44.32
STATCOM	103.7	16.32	267.65	43.49
SSSC	111.33	20.84	303.33	62.73
UPFC	111.4	20.88	303.66	63.64

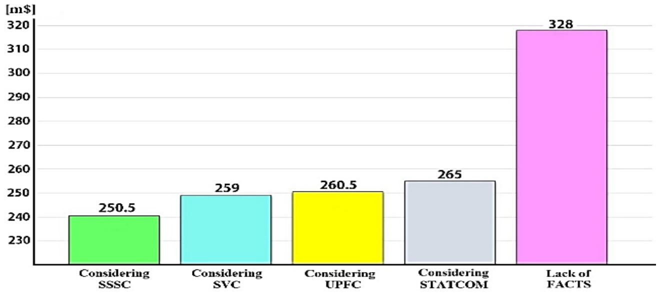

Fig. 13. Overview of current equivalent to the amount of investment required for the expansion of the transmission section of 9 bus power system in different states.

B. Implementation of Proposed Method on 39-Bus Power System

After the desired results were achieved in the previous for bus 9 power system, the proposed method was evaluated on the 39-bus power system overviewed in Figure 14. Planned 16-year horizon is divided in two 8-year periods (first and second expansion plans). The results of the implementation of the proposed algorithm on power system bus 39 are shown below.

1) TEP in the case of lack of FACTS devices for 39 bus power system.

a) First expansion plan-no FACTS devices

In this expansion, a total of 571 km of new 345 kV line is necessary to construct .In the expansion plan, it is necessary to expand a total of about 7100 MVA in the transformer section. According to the results, the overall cost of the first expansion plan is 1026 million.

b) Second expansion with FACTS devices

In this expansion, a total of 906 km of new 345 kV line is necessary to construct .In the expansion plan, it is necessary to expand a total of about 9400 MVA done in the transformer section. The total cost of the second plan was 1617 million. The equivalent of today's (with an interest rate of 10%) 754 million. Today's equivalent of the sum of investments during the first and second expansion plans is 1.78 billion.

2) Considering SVC in TEP

a) The first expansion plan considering SVC

Due to technical limitations the possibility of setting up to five SVC devices in bus 4, 7, 12, 15 and 27 was assumed. It is important to optimize the number and location of the SVC candidates to minimize the cost of the expansion. The locating of SVC devices was done by using the proposed backward method and the steps of the process are given in Table VII. It should be noted that during the 3rd stage of expansion the elimination of candidate 7 compared to the elimination of candidate 27 lead to 5MW smaller real power losses, so that's why the elimination of candidate 7 is a top priority. Therefore, the optimal location in the first expansion plan is the construction of two SVC in buses 12 and 15. In this expansion, a total of 489 km of new 345 kV line is necessary to construct. In the expansion plan, it is necessary to expand a total of about 5500 MVA in the transformer section. In this plan, the total cost of FACTS devices has been 40 million. The total cost of the first expansion plan including the total cost of FACTS devices is 904 million.

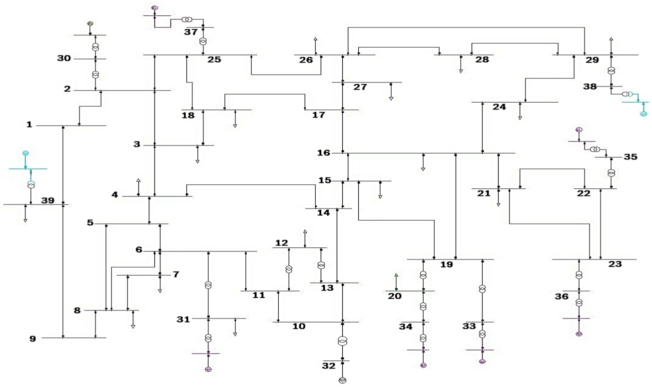

Fig. 14. Basic power system of 39 bus system

TABLE VII. LOCATING OF SVC DEVICES USING BACKWARD METHOD IN FIRST EXPANSION PLAN

Stage	Eliminated Candidate (SVC)	Remaining Candidates (SVC)	Total Cost For First Expansion Plan [m$]
1	*initial state*	4-7-12-15-27	945
2	4	7-12-15-27	928
	7	4-12-15-27	933
	12	4-7-15-27	957
	15	4-7-12-27	991
	27	4-7-12-15	933
3	7	12-15-27	916
	12	7-15-27	978
	15	7-12-27	974
	27	7-12-15	916
4	12	15-27	928
	15	12-27	962
	27	12-15	904
5	15	12	950
	12	15	916
6	15	No candidate	1026

b) The second expansion plan considering SVC

Results for optimal locating of SVC using backward method are given in Table VIII.

TABLE VIII. LOCATING OF SVC DEVICES USING BACKWARD METHOD IN SECOND EXPANSION PLAN

Stage	Eliminated Candidate (SVC)	Remaining Candidate (SVC)	Total Cost For First Expansion Plan [m$]
1	initial state	4-7-27	1632
2	4	7-27	1615
	7	4-27	1620
	27	4-7	1620
3	7	27	1608
	27	7	1603
4	7	No candidate	1591

As result, none of the establishment of remaining SVCs (candidates) cost will be reduced. So, the most economical mode of the second expansion plan, is not adding any more SVCs to the SVCs built in the first expansion. In this expansion, a total of 895 km of new 345 kV line was necessary to construct. It was necessary to expand a total of about 9000 MVA in the transformer section. The total cost of the second plan was 1591 million. The equivalent of today's (with an interest rate of 10%) of 742 million. Today's equivalent of the investment sum during the first and second expansion plans was 1.646 billion.

3) Considering SSSC in TEP

a) First expansion plan considering SSSC

Assuming the possibility that due to technical limitations, up to five SSSC devices in lines 5, 7, 15, 25 and 32 could be set up. Results for optimal locating of SSSCs by using the backward method are given in Table IX. Thus, the optimal state in the first expansion plan, will be the construction of three SSSC devices, in lines 5, 15 and 25. Mentioned lines are between the buses 23-21, 19-15 and 29-24 respectively. In this expansion, a total of 398 km of new 345 kV line are necessary to construct. In the expansion plan, it is necessary to expand a total of about 6400 MVA in the transformer section. The total cost of FACTS constructed was 90 million. The total cost of the first expansion plan including the total cost of FACTS was 825 million.

TABLE IX. LOCATING OF SSSC DEVICES USING BACKWARD METHOD IN FIRST EXPANSION PLAN

Stage	Eliminated Candidate (SSSC)	Remaining Candidates (SSSC)	Total Cost For First Expansion Plan [m$]
1	initial state	5-7-15-25-32	885
2	5	7-15-25-32	957
	7	5-15-25-32	861
	15	5-7-25-32	953
	25	5-7-15-32	957
	32	5-7-15-25	855
3	5	7-15-25	876
	7	5-15-25	825
	15	5-7-25	876
	25	5-7-15	890
4	5	15-25	908
	15	5-25	897
	25	5-15	908
5	5	25	1056
	25	5	1059
6	25	No candidate	1026

b) Second expansion plan considering SSSC

Results for optimal locating of SSSC by using the backward method are given in Table X. Based on the results obtained, the optimal mode corresponding to the construction of a new SSSC device will be in line 32 (between buses 6 and 8). In this expansion, a total of 528 km of new 345 kV line is necessary to construct. In the expansion plan, it is necessary to expand a total of about 9800 MVA in the transformer section. The total cost of FACTS devices was 30 million. The total cost of the second plan was 961 million. The today's equivalent of (with an interest rate of 10%) 448 million. Today's equivalent of the sum of investments during the first and second expansion plans, is 1.273 billion. Comparison of the costs of today's equivalent of total investments in various states of expansion (lack of FACTS, considering SVC and SSSC) for 39-bus power system is shown in Figure 15. According to the results shown in Figure 15, by the construction of two SVC devices during the first eight years, and not adding devices during the second eight year period, the total economic savings of 134 million will be achieved. However, with the construction of three SSSC devices during the first eight years, and the construction of one SSSC during the second eight years, the total savings will rise up to 507 million. In addition to the above, by the increased reduction of lines, the occurrence probability occurrence of the undesirable N-1 contingency will also be reduced.

TABLE X. LOCATING OF SSSC DEVICES USING BACKWARD METHOD IN SECOND EXPANSION PLAN

stage	Eliminated Candidate (SSSC)	Remaining Candidates (SSSC)	Total Cost For First Expansion Plan [m$]
1	initial state	7-32	991
2	7	32	961
	32	7	115
3	32	No candidate	1117

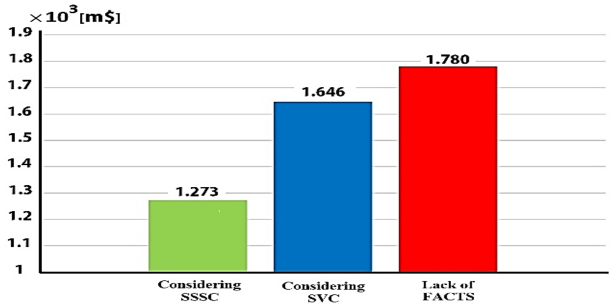

Fig. 15. Today's equivalent of the total investment costs of the transmission section of 39-bus power system

V. CONCLUSION

Including FACTS devices in transmission system expansion planning leads to a more effective operation of the power system which results to a significant reduction in investment costs. Series FACTS devices (SSSC and UPFC) seem to provide the best results due to the real power and reactive power flow control in line including the series portion of these devices. The optimal expansion of the transmission system with the use of FACTS sometimes increases the need to expand the transformer sections but it is desirable because it is associated with a sharp decline of total costs in line constructions. However, a certain limit to this trade-off is to be considered. Determining the optimal number and location of FACTS devices is essential for the optimization. This paper focuses on implementing a method based on sensitivity analysis to select the optimal number and location of FACTS devices, lines and other elements of the transmission system. The method was employed in a 9 and a 39 bus power system and results are shown and discussed.

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