Application of FACTS Devices in Transmission Expansion Planning to Overcome Problems of Projects Delays

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***Abstract* -- This paper takes delays in transmission projects into consideration. The low voltages and congested lines are main problems of project delays. In this paper, FACTS devices are chosen as the best solution to overcome these problems. In the paper, an algorithm is suggested as a mean to investigate the transmission expansion candidate plans, and to find the most robust plan against the problems of the delays. In this procedure, the worst scenario for each candidate is determined, and FACTS devices are allocated. The proposed procedure is applied to Garver's and RTS networks.**

***Index Terms*— Candidate, Delay, FACTS, Scenario, Sensitivity analysis, Transmission Expansion Planning.**

1. Introduction

Power transmission systems have been established in order to deliver power from generation system to demand sites. By growing the demand for electrical energy, transmission system expansion looks inevitable in order to provide energy for consumers. Due to technological complexity and great cost of the procedure, hundreds of papers have been published, and tried to provide a model for this problem, and solve it optimally. In regulated systems, the goal of Transmission Expansion Planning (TEP) is to find the least-cost plan for network expansion, in order to provide consumers with reliable energy. In the beginning of studies, large simplifications had been considered. For example, the circuitry laws of network were underestimated by transportation or dc models. Most of these models had been optimized by mathematical tools like linear programming [1-5]. By evolution in computers, and development of heuristic optimization methods, some of the simplifications have been eliminated [6-9], e.g., AC power flow instead of DC one.

Many researches were concentrated on more precise models for TEP, and methods to optimize them [10]. After presentation of the idea of restructuring, the goal of TEP has been diverted to reach a future network, which provides the market with the ability to reach the maximum global welfare [11]. Moreover, the assumptions of TEP have been totally changed. Therefore, most of the recent publications have tried to propose models adaptive to the new problem, which has higher level of uncertainty in assumptions. In some publications, one of these uncertainties was taken into consideration. Therefore, the models are still far from what happens in practice. One of the most serious problems, with which power system planners and investors often encounter, is the project delay in constructing and commissioning of new plans. The causes and effects of such delays will be studied in this paper. In addition, an algorithm is proposed in order to optimally locate suitable FACTS to increase the flexibility of the plan and consequently, decrease the problems of delay in commissioning.

2. Delays; causes and effects

One major problem of each power system designer is the delay in commissioning of new plans. Such delays force them to utilize the system in a critical operating point. Congestion of existing lines, and low voltages at receiving ends, especially during contingencies, are direct results of these delays. However, the end effect may even be worse, and ends in cascading trips and black- out.

Some major causes of these delays are listed bellow:

a- Evolution of financial parameters

b- Licensing for new facilities

c- Obtaining right-of-way

d- Delay in decision making

The unexpected changes in equipments costs and exchange rates are examples of the evolution of financial parameters. According to CIGRE's working group 37.10, the main specific problem for the transmission system appears to be excessive delays is obtaining right-of-way for new lines [12]. Delay in decision making occurs mostly because of uncertain parameters such as demand evolution rate, future load locations and trading potentials. According to [13], one year delay in transmission permitting by federal agencies is usual in the United States' Western grid. Therefore not only developing countries but also well developed countries suffer from delays in transmission system expansion. The problem is so serious and commonplace that Western Electricity Coordinating Council has assigned the Planning Coordination Committee, the responsibility to identify the types and investigate the impact of delay on the timing and availability of power generation and transmission facilities [14]. Also, European Union's Energy Committee announced that twenty out of the thirty two prior projects in Europe that are power-related are already delayed. Twelve of those twenty face to a one- or two-year delay, while eight are looking at delays of three or more years.

3. FACTS DEVICES; FLEXIBILITY FOR NETWORKS

As it is mentioned before, the most important impact of delay is over-loading of some transmission lines and decrease of voltages of some bus bars under standard value. In such cases, the control of the power flow, i.e. the ability of redispatch of power and the injection of reactive power can play a key role to increase the network security. Flexible AC Transmission System (FACTS) devices are the most suitable means of network security enhancement in such cases. Although shunt and series capacitors and reactors have the ability to change the voltage profile and power flow pattern, but they are not so fast as FACTS elements. Another demerit of such passive elements in comparison to FACTS devices are their discontinuous range of operation, and as a result, they can not be used for fine regulations. Series FACTS devices can decrease or increase the power flow of a certain line according to the scenario happened, and then, predetermination of the scenario which is impossible in expansion planning is not necessary. The last but not the least important advantage of the FACTS devices, which makes them appropriate means to handle problem related to delays, is their relocatability. Today, there are several commercially available FACTS, which are built into movable containers. They can be easily transported to any location in the network [15]. Consequently, transmission system planners can order such devices from the beginning of the expansion procedure to twelve month before the horizon without allocating them. At the horizon of planning, and near precise determination of uncertain parameters and delays, planners will decide when and where to instal them. In the following, the ability of Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR) and Static VAR Compensators (SVC) to overcome problems related to delays will be studied.

4. PROPOSED ALGORITHM TO DECREASE NEGATIVE IMPACTS OF DELAYS

Usually, the optimization of each planning model, will leads to a set of quasi optimal candidates of transmission expansion. The procedure proposed here is simulated for each candidate, and finally the most flexible candidate will be introduced. The procedure is as follows:

Step1: After the ordinary planning of the system, all possible scenarios should be simulated for each candidate, and the worst condition should be determined. Each scenario includes the delay in commissioning of one of the future lines, and a single contingency simultaneously. To identify the worst condition, a Performance Index (PI) will be assigned and calculated for each scenario. The severity of system loadings will be evaluated using the following PI:

$$PI = \sum_{m=1}^{N_L} \frac{w_m}{2n} \left(\frac{P_{Lm}}{P_{Lm}^{\max}}\right)^{2n} \qquad (1)$$

Where P_{Lm} is the real power flow, P_{Lm}^{max} is the rated capacity of m-th line. n is the exponent, and w_m is a nonnegative coefficient may be used to present the importance of line.

Step 2: In this step FACTS devices are optimally located for the worst scenario of each candidate in order to eliminate the congestions and under-voltages. (The process of allocation will be described in the next secion.)

Step 3: The robustness of each candidate after the installation of FACTS devices against the possible delays will be determined.

Step 4: The plan which can satisfy the planners' objective, and is flexible enough to deal with the delays, will be chosen in this step.

5. LOCATION OF FACTS DEVICES

This procedure will be fulfilled after determination of the worst scenario for each candidate, i.e. step1. If one of the lines is overloaded, sensitivity of this line to changes in the power flow of other lines will be calculated. TCSC or TCPAR will be located on the line which has the highest sensitivity coefficient. In case that two or more lines are overloaded, TCSC or TCPAR will be located in order to decrease PI as much as possible. So, the following PI sensitivity coefficients should be calculated for TCSC installation:

$$b_k = \left.\frac{\partial PI}{\partial x_{ck}}\right|_{x_{ck}=0} \qquad \text{(for } k=1,2,..,N_L\text{)} \qquad (2)$$

Where b_k is the sensitivity factor of PI to TCSC parameter, which is installed at line k between buses i and j. Choosing $n=2$, results in the following equation:

$$\frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_L} w_m P_{Lm}^3 \left(\frac{1}{P_{Lm}^{\max}}\right)^4 \qquad (3)$$

Based on the DC power flow equations, P_{Lm} can be calculated as bellow [16]:

$$P_{Lm} = \begin{cases} \sum_{n=1, n\neq S} S_{mn} Pn & \text{for } m\neq k \\ \sum_{n=1, n\neq S} S_{mn} Pn + P_j & \text{for } m=k \end{cases} \qquad (4)$$

Where n is the number of buses and S is the reference bus.

Therefore, we have:

$$\frac{\partial P_{Lm}}{\partial x_{ck}} = \begin{cases} (S_{mi}\frac{\partial P_i}{\partial x_{ck}} + S_{mj}\frac{\partial P_j}{\partial x_{ck}}) & \text{for } m \neq k \\ (S_{mi}\frac{\partial P_i}{\partial x_{ck}} + S_{mj}\frac{\partial P_j}{\partial x_{ck}}) + \frac{\partial P_j}{\partial x_{ck}} & \text{for } m = k \end{cases} \tag{5}$$

Where:

$$\left.\frac{\partial P_i}{\partial x_{ck}}\right|_{x_{ck}=0} = \left.\frac{\partial P_{ic}}{\partial x_{ck}}\right|_{x_{ck}=0} \approx -\frac{\delta_{ij}}{x_{ij}^2} \tag{6}$$

And

$$\left.\frac{\partial P_j}{\partial x_{ck}}\right|_{x_{ck}=0} = \left.\frac{\partial P_{jc}}{\partial x_{ck}}\right|_{x_{ck}=0} \approx \frac{\delta_{ij}}{x_{ij}^2} \tag{7}$$

Although the exact calculations of PI sensitivity coefficients based on AC load flow have been presented in [17], but the above calculations are precise enough to find the best place for TCSC. Then, the line which has maximum absolute sensitivity is chosen, and TCSC is placed on it. If the sensitivity is negative, TCSC should be operated in capacitive mode and vise versa.

For TCPAR, the calculations are almost the same as TCSC but the equations (2), (6) and (7) should be replaced by following equations, respectively:

$$b_k = \left.\frac{\partial PI}{\partial \phi_k}\right|_{\phi_k=0} \qquad \text{(for } k=1,2,..,N_L\text{)} \tag{8}$$

$$\left.\frac{\partial P_i}{\partial \phi_k}\right|_{\phi_k=0} = \left.\frac{\partial P_{is}}{\partial \phi_k}\right|_{\phi_k=0} = V_i V_j (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \tag{9}$$

$$\left.\frac{\partial P_i}{\partial \phi_k}\right|_{\phi_k=0} = \left.\frac{\partial P_{is}}{\partial \phi_k}\right|_{\phi_k=0} = -V_i V_j (G_{ij}\sin\delta_{ij} + B_{ij}\cos\delta_{ij}) \tag{10}$$

After locating TCSC or TCPAR, the modified network should be simulated again, and SVCs are installed at the buses with voltage problem.

6. CASE STUDY

6-1 Garver's 6-bus Test System:

This system is shown in Fig. 1. In this section, the proposed algorithm is applied to 17 candidate plans for expansion of Garver's system. These plans are the results of running a Genetic Algorithm (GA) - based program in a vertically oriented environment. The cost function of the model, which should be minimized, is the total cost of construction and operation of the future network. These plans are listed in Table 1. The results of applying the proposed algorithm to plans 2, 12, and 17 are discussed here.

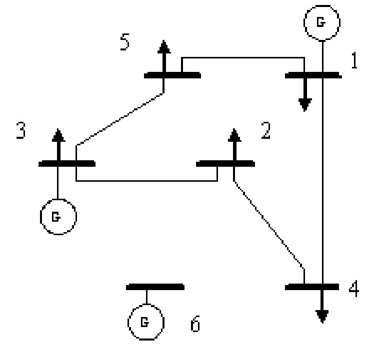

Fig. 1: Garver's 6-bus system

Table 1: Expansion candidates of Garver's system

	From bus	1	2	2	3	6	6	6	6
	To bus	5	3	5	5	2	3	4	5
Plan No.	1	...	1	...	1	...	...	4	...
	2	...	1	...	2	1	...	3	...
	3	...	1	...	2	2	...	2	...
	4	1	1	...	1	2	...	2	...
	5	...	2	...	1	1	...	3	...
	6	...	2	...	1	...	...	4	...
	7	1	1	...	1	...	...	4	...
	8	...	1	...	2	...	...	4	...
	9	1	1	...	1	1	...	3	...
	10	...	1	...	1	...	...	5	...
	11	...	1	...	1	...	...	3	1
	12	...	1	1	1	1	...	3	...
	13	...	1	...	1	1	...	2	1
	14	...	1	1	1	2	...	2	...
	15	1	1	...	1	1	1	2	...
	16	...	1	...	2	1	1	2	...
	17	...	2	...	1	...	1	3	...

Plan #2: This plan will have seven new lines in addition to its five existing lines. PI analysis shows that the worst condition will happen if new line between buses 2 and 3 is commissioned with delay, and during this delay a contingency put the existing line between 2 and 3 out of service. Under these circumstances, the most serious problem is the 86% overloading of the line 2-6.

After PI sensitivity analysis, it seems that placing a TCPAR on the line between buses 2 and 4, may enhance the security of the network. However, the simulation shows that even in the presence of TCPAR, 73% of the overload remains.

To increase the voltage of bus 2 upper than .9 p.u., an unreasonable 126MVAR injection in bus 2 is necessary. Moreover, it is obvious that 73% overloading of line 2-6 will lead this line to be tripped. Then, tripping of the line 2-4 will happen. Another alternative is the load shedding in bus 2, which is undesirable.

Plan #12: The same as plan #2, this future network will consist of seven new lines in addition to its five existing lines. To this plan, the worst scenario is the tripping of the new line 2-6 in the absence of new line between 2 and 3. In this case, Furthermore, 26% overloading occurs on line 2-3. After installation of a TCPAR on line 2-3, all lines will be loaded bellow their nominal rates. As a result, no load shedding is needed. In addition, by injecting 60MVAR at bus 2 by installing a SVC, the voltage of bus 2 will reach 0.9 p.u.

Plan #17: This plan includes one more line in comparison to plan #12. When the worst scenario occurs, i.e. one of the future lines in corridor 6-4 encounters with delay and a contingency puts the existing line in 2-4 out of service, the system has a voltage collapse, and FACTS devices are unable to overcome this problem.

6-2 RTS 24-bus System:

The parameters of IEEE 24-bus Reliability Test System (RTS) are given in [18]. In [19], a strategy for transmission expansion under a competitive market environment has been proposed, and four candidates for RTS future network have been offered. These plans are listed in Table 2.

Table 2: Expansion candidates of RTS

Line added	Number of line added			
	pl1	*pl2*	*pl3*	*pl4*
1-5	1		1	
3-24	1	1	1	1
6-10	1	1	1	1
7-8	3	1	2	2
10-12		1	1	1
12-13				1
14-16	1	1		1
15-21	1	1		
15-24	1	1		1
16-17	2	2	1	1
16-19	1			
17-18	1	1		
2-8		1		
14-23			1	

Plan #1: the forced outage of the existing line in corridor 15-24 during the delay in commissioning of the new line in this corridor results in the worst condition. In this case, 25% overloading happens to line 3-9. Sensitivity analysis reveals that power flow of line 3-9 is highly sensitive to increasing the flow of line 1-3. Therefore, installing TCSC at line 1-3 seems the best solution. When the firing angel is set in a way that TCSC acts like a capacitive impedance, the loading of line 3-9 decrease bellow its nominal rate. However, in this case an over voltage equal to 0.08 p.u. occurs in line 1-3. To overcome this problem, a SVC is installed at this point. Absorbing 18MVAR results in the voltage is decrease to 1.05 p.u. which is acceptable.

Plan # 3: This plan includes seven future lines in addition to its existing lines. PI analysis demonstrates that the worst scenario is thee forced outage of line 14-16 in the absence of future line in corridor 14-23. Under these conditions, overloads equal to 18% and 7% occur in lines 15-24 and 3-9 respectively. This problem can be easily solved by installation of a TCSC in reactive mode in line 15-24. In this case, voltages of all buses are within standard limits.

7. Conclusion

In this paper, the delay in transmission projects, its causes and effects have been studied. An algorithm has been proposed to overcome the problems related to such delay too. This algorithm is based on the application of FACTS devices. The following items can be concluded from case studies:

a: Considering plan 2 of section 6-1, it is obvious that the best solution for the traditional expansion problem is the most vulnerable candidate in cases that a delay occurs. Moreover, in small networks, FACTS devices can not overcome the delay-related problems. So, the overdesign is necessary. However, these devices can decrease the extent of overdesign system.

b: Comparing plans of sections 6-1 and 6-2, it can be concluded that the plans with more lines is not necessarily more robust than a plan with fewer. In the other words, in addition to number of lines, their arrangement is also an effective factor.

c: Comparing plans of sections 6-1 and 6-2 shows that large networks are more robust than small ones. In such system, low voltages barely happen due to delays, and congestion is the major problem. In addition, planners of deregulated systems try to minimize congestion and provide more paths in order to remove the market power. As a result, the market-based plans can have enough security by utilizing FACTS devices in case of project delay.

d: Although TCSC can effectively decrease or even totally remove the congestions, it may result in overvoltage of the compensated line.

e: The ability of FACTS devices to manage both active and reactive powers makes them a superior solution to overcome the impacts of the delay in transmission projects.

I. References

[1] R. S. CHANDA, P. K. BHATTACHARJEE, "Application of computer software in transmission expansión planning using variable load structure", *Electric Power Systems Research*, no. 31, pp. 13–20, 1994.

[2] K. J. KIM, Y. M. PARK, K. Y. LEE, "Optimal long term transmission expansion planning based on maximum principle," *IEEE Trans. Power Syst.*, vol. 3, pp. 1494–1501, Nov. 1988.

[3] R. VILLASANA, L. L. GARVER, S. L. SALON, "Transmission network planning using linear programming," *IEEE Trans. Power Apparat. Syst.*, vol. PAS-104, pp. 349–356, Feb. 1985.

[4] L. L. GARVER, "Transmission network estimation using linear programming," *IEEE Trans. Power Apparat. Syst.*, vol. PAS-89, pp. 1688–1697, Sept./Oct. 1970.

[5] J. C. KALTENBATCH, J. PESHON, E. H. GEHRIG, "A mathematical optimization technique for the expansion of electrical power transmission systems," *IEEE Trans. Power Apparat. Syst.*, vol. PAS-89, pp. 113–119, Feb. 1970.

[6]E. L. DA SILVA, H. A. GIL, J. M. AREIZA, "Transmission network expansion planning under an improved genetic algorithm," *IEEE Trans.*
Power Syst., vol. 15, pp. 1168–1175, Aug. 2000.

[7] J. Contreras and F. F.Wu, “A kernel-oriented algorithm for transmission expansion planning,” *IEEE Trans. Power Syst.*, vol. 15, pp. 1434–1440, Nov. 2000.
[8] R. A. GALLEGO, A. B. ALVES, A. MONTICELLI, R. ROMERO, “Parallel simulated annealing applied to long term transmission network expansion planning,” *IEEE Trans. Power Syst.*, vol. 12, pp. 181–188, Feb. 1997.
[9] R. ROMERO, R. A. GALLEGO, A. MONTICELLI, “Transmission system expansion planning by simulated annealing,” *IEEE Trans. Power Syst.*, vol. 11, pp. 364–369, Feb. 1996.
[10] G. LATORRE, R. D. CRUZ, J. M. AREIZA, A. VILLEGAS, “Classification of Publications and Models on Transmission Expansion Planning,” *IEEE Trans. Power Syst.*, vol. 18, pp. 938–946, May. 2003.
[11] F.F WU, F.L. ZHENG, F.S. WEN “Transmission investment and expansion planning in a restructured electricity market” , Elsevier, Energy 31, pp. 954–966, 2006
[12] CIGRE WORKING GROUP 37.10, "Dealing with uncertainty in system planning" ELECTRA n° 151, December 1993
[13] National Association of Regulatory Utility Commissioners, “State of the Nation’s Electric Transmission Grid”, Jul. 2008.
[14] M.VAKILIAN, R.C.DEGENEFF “ColumbiaGrid Involvement in Regional and Sub-regional Planning”, ColumbiaGrid, Apr. 2008.
[15] C. SCHAFFNER, G. ANDERSSON, “Determining the value of controllable devices in a liberalized electricity market: a new approach” Power Tech Conference Proceedings, *IEEE*, Bologna, 2003.
[16] A.J. WOOD, B.F. WOLLENBERG, “Power Generation, Operation and Control”, John Wiley, New York, 1996.
[17] S.A. TAHER, H. BESHARAT, “Transmission Congestion Management by Determining Optimal Location of FACTS Devices in Deregulated Power System”, American Journal of Applied Science 5(3), pp. 242-247, 2008.
[18] Reliability test system task force of the application of probability methods subcommittee, “IEEE reliability test system,” *IEEE Trans. Power App. Syst.*, vol. PAS-98, pp. 2047–2054, Nov./Dec. 1979.
[19] R. FANG, D. J. HILL, “A New Strategy for Transmission Expansion in Competitive Electricity Markets", *IEEE Trans. Power Syst.*, vol. 18, No. 1, Feb. 2003.