Flexible Transmission Network Planning with Post-Contingency Network Switching

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***Abstract*- Power systems are set to undergo dramatic changes driven by many factors ranging from climate change to technological developments. It is expected that networks will become smarter and more flexible able to deal with uncertainties in future generation types and locations as well as system operation practices within liberalized electricity markets. This will include energy storage and demand response as extra system control options. These developments will require a fundamental change in the way power systems are planned. This paper introduces the concept of flexible transmission network planning which, in contrast to current network planning under the so-called preventive control, network switching as a plausible corrective control action is assumed in the course of network planning. A practical model for switchable substations is also proposed. A discrete transmission investment model is applied to reflect real life scenarios. In order to deal with the scale of the problem a multi-stage solution algorithm is proposed combining heuristic techniques and a Genetic Algorithm. The proposed approach is implemented on the IEEE 24 bus test system and its superiority to conventional method is demonstrated.**

***Index Terms*-- Transmission Expansion, Corrective Control, Flexible Network, Network Rescheduling.**

I. INTRODUCTION

Transmission network expansion is one of the major challenges facing modern power systems. Difficulties in obtaining rights of way to construct new transmission lines as well as high costs associated with network expansion make transmission line projects problematic and often behind schedule. In order to circumvent these costly and time-consuming transmission expansion projects, power system planners tend to take those approaches which aim to use the network assets as efficiently as possible.

In the transmission network planning (TNP) one of the concerns is the security constraint which dictates that outage of every single transmission line should not disrupt the transmission of energy from supply sources to consumers. Traditionally, TNP has been based on the assumption that the system will be operated in the so-called preventive mode where the network is secured against credible line outages [1]. Planning networks in this way invariably leads to considerable overcapacity which is only used infrequently when a contingency occurs.

Some corrective actions such as network switching are usually used by operators heuristically to relieve overload problems in a given network [2-4]. However, network planners usually ignore network switching as their objective is to propose a network which can survive all likely contingencies without taking any particular action. The main reason for the reluctance of planners to deploy network switching to deal with contingencies is the absence of reliable and intelligent wide area communication and control systems able to reconfigure the network swiftly. Nevertheless, the need for flexible and intelligent networks popularly referred to as smart or thinking networks is being addressed by researchers [5, 6]. It seems inevitable that intelligent systems underpinned by wide area monitoring, communication and control will grow and become a key feature of future power systems. These developments will facilitate the deployment of an intelligent network switching in the near future. Consequently network reconfiguration ability is a plausible assumption in the course of TNP.

In this paper, by taking advantage of the network switching, a practical approach for transmission network planning is introduced. The objective is to find the optimum transmission investment as well as optimum operation cost for a given network assuming that network switching is a plausible network control option. The solution should be able to meet every single credible line outage while respecting the physical laws that govern electric power systems as well as limits on power system components. Taking a realistic assumption, all substation models are assumed to be double bus-double breaker, and also due to the lumpy nature of transmission investments, discrete values are considered for credible capacities of lines. As this is a large scale problem it is proposed to decompose it first and apply an iterative multi-stage solution method. Genetic Algorithm (GA) as a part of that multi-stage method is used to find the best switching patterns. Application of the proposed method is demonstrated on the IEEE 24 bus RTS and results show the superiority of the method over other conventional methods.

The remainder of the paper is organized as follows: in the next section the conventional objective function in TNP is introduced. Section III details the proposed network switching strategy. TNP with post-contingency network switching is elaborated in section IV. Numerical studies are given in section V and finally the main conclusions are summarized in VI.

II. CONVENTIONAL TNP APPROACH

The main aim in conventional TNP is to find the optimum capacity of candidate transmission lines along with optimum generation dispatch [7]. The objective function is mathematically expressed as follows:

This work is funded by the Supergen FlexNet Consortium (supergen-networks.org.uk) a part of the UK Research Councils' Energy Programme under grant EP/E04011X/1.

$$\underset{G_i, P_{\max i}}{Minimize} : \sum_{i=1}^{Ng} C_i.G_i + \sum_{i=1}^{N_l} T_{mi}.l_i.P_{\max i} \qquad (1)$$

Where

C_i : Incremental cost of generator i (€/MWh)

G_i : Power generated by generator i (MW)

T_{mi} : Annuitized investment cost of line i (€/Km.MW.year)

l_i : Length of transmission line i (km)

$P_{\max i}$: Maximum capacity of transmission line i (MW)

N_l : Number of transmission lines

N_g : Number of generators

Also Kirchhoff's first and second laws should be respected as well as component limits in the power system. Therefore, in a DC model, the objective function (1) is subject to the following constraints:

$$\sum_{\forall i \in N_{gd}} G_i + \sum_{\forall i \in N_{ld}} P_i - L_d = 0 \qquad d = 1,\ldots,N_b \qquad (2)$$

$$P_i - \frac{(\theta_k - \theta_l)}{X_i} = 0 \qquad i = 1,\ldots,N_l \qquad (3)$$

$$-P_{\max i} \le P_i \le P_{\max i} \qquad i = 1,\ldots,N_l \qquad (4)$$

$$G_{\min i} \le G_i \le G_{\max i} \qquad i = 1,\ldots,N_g \qquad (5)$$

Where

L_d : Load demand at bus d (MW)

P_i : Power flowing in transmission line i (MW)

θ_k : Voltage angle of bus k (radian)

X_i : Admittance of transmission line i (p.u.)

$G_{\max i}, G_{\min i}$: Maximum and Minimum output of generator i (MW)

N_b : Number of buses

N_{gd} : Set of generators connected to bus d

N_{ld} : Set of lines connected to bus d

(2) to (5) should be satisfied for both intact and contingent networks. $P_{\max i}$ and G_i are coupling decision variables between normal and contingency states. $P_{\max i}$ is the maximum limit of the transmission line i and remains fixed in all system states. Also, if a line outage occurs the generation dispatch should be kept unchanged as generator operating characteristics do not allow generators to change their output power within the timescales required to resolve the network constraints.

It should be noted that (1) is a linear optimization problem in which transmission capacities are treated as continuous variables. However, due to the lumpy nature of transmission investment, it is often not possible to build a transmission line whose rating exactly matches the resultant capacity of the above optimization. In a real-life case, the practical transmission capacity (PTC) of an overhead line usually follows a stepwise model shown in Fig. 1. In Fig. 1, the horizontal axis shows the optimum capacity which is the outcome of optimization (1) whereas the vertical axis shows the PTC. For instance, if the resultant optimum capacity for line i ($P_{\max i}$) is an amount greater than L_1 and less than or equal to L_2, an overhead line with a capacity of L_2 should be constructed (PTC= L_2).

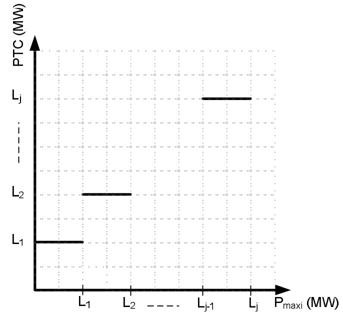

FIG. 1. STEPWISE MODEL FOR TRANSMISSION INVESTMENT

III. NETWORK SWITCHING

Network switching is widely used by operators to resolve problems in power systems. In this regard, many studies have been conducted to show the application of network switching can remove overloads and voltage violations [2], to enhance the network security [7] and to survive blackout [8]. Almost all these studies have been carried out on a transmission network of which the capacity was known. In this study, however, a different application of network reconfiguration is presented. The aim is to find the optimum transmission capacity as well as generation dispatch assuming the network switching as a completely credible post contingency control action.

Different types of switching strategy may be considered regarding the substation arrangement [4]. In this study, a double bus-double breaker model illustrated in Fig. 2 is assumed for those substations meant to be switchable. As shown in Fig. 2, two breakers are allocated for a line connected to a substation. With this arrangement three different connection states may occur. For instance, line T1 may be connected to either Bus A or Bus B or neither, see Table 1. In this study generators and loads are assumed to be connected to Bus A.

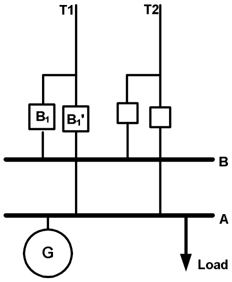

Fig. 2. Double bus-double breaker model for the substation

Table I
Different connection states for line T1 shown in Fig. 1

Line's connection State code	B_1	B_1'	Connected to
1	Closed	Open	Bus B
2	Open	Closed	Bus A
3	Open	Open	Disconnected

IV. TNP WITH NETWORK SWITCHING PARADIGM

This section presented the proposed approach which, by taking advantage of network switching, achieves a more economic transmission expansion plan than the conventional approach described in Section II. The proposed method is able to find the best switching pattern for the intact network as well as all contingent networks so that operation and investment costs are minimized.

TNP with network switching is a large scale optimization problem having many integer and continuous variables. In order to deal with the dimension of this problem a three stage iterative approach is used to literally decompose the problem and turn it into several solvable sub-problems. The three stages are explained below.

A. Stage I: Minimum Transmission Capacity Calculation

This stage is meant to heuristically calculate the minimum required capacity ($P_{\min i}^{(k)}$) at the beginning of each iteration.

For kth iteration, the minimum required capacities are calculated using a heuristic technique which can be expressed by two rules given below.

Rule1:

$$if \quad \left|P_{avg_i}^{(k)} - L_{j-1}\right| \le \left|P_{avg_i}^{(k)} - L_j\right| \quad then \quad P_{\min i}^{(k)} = L_{j-1}$$

$$else \;\; P_{\min i}^{(k)} = L_j$$

Rule2:

$$if \;\; \forall i \;\; P_{\min i}^{(k)} = P_{\min i}^{(k-1)} \quad then \;\; \forall i \, P_{jumpi}^{(k)} = P_{avgi}^{(k)} - P_{\min i}^{(k)}$$

$$for \;\; transmission \; line \;\; i \;\; having \;\; the \; biggest \;\; P_{jumpi}^{(k)}$$

$$do \;\; P_{avgi}^{(k)} = L_j$$

$$where \;\; L_j > P_{avgi}^{(k)} \;\; and \;\; L_j \;\; is \; the \; closest \; PTC \; to \;\; P_{avgi}^{(k)}$$

$P_{avgi}^{(k)}$ is the average of optimal capacities for line i which are proposed by stage II and stage III in kth iteration, it is mathematically shown by (13), $P_{\min i}^{(k)}$ denotes the minimum required capacity for transmission line i in kth iteration. For the first iteration the minimum capacity is assumed to be zero for all lines. Also, L_j and L_{j-1} refer to the horizontal axis of Fig 1.

The resultant minimum capacities are sent to stage II and stage III which are elaborated below.

A. Stage-II: Intact Network

Stage II applies the well known Genetic Algorithm [8] as finds the best switching pattern in the intact network so that the minimum transmission investment and operation cost are achieved. The fitness of each chromosome which represents a particular network topology is the minimum operating and investment cost (6). This problem is similar to conventional TNP problem described in section II, but in this case an extra inequality constraint (11) is added. Constraint (11) says that the maximum transmission capacity cannot be less than the transmission capacity proposed by stage I.

$$\underset{G_i, P_{\max i}}{Minimize} \; : Fitness_{stage-II} = \sum_{i=1}^{Ng} C_i.G_i^{(k)} + \sum_{i=1}^{N_l} T_{mi}.l_i.P_{\max i}^{net(k)} \qquad (6)$$

Subject to:

$$\sum_{\forall i \in N_{gd}} G_i^{(k)} + \sum_{\forall i \in N_{ld}} P_i^{(k)} - L_d = 0 \qquad d = 1,\ldots,N_b \qquad (7)$$

$$P_i^{(k)} - \frac{\left(\theta_k^{(k)} - \theta_l^{(k)}\right)}{X_i} = 0 \qquad i = 1,\ldots,N_l \qquad (8)$$

$$-P_{\max i}^{net(k)} \le P_i^{(k)} \le P_{\max i}^{net(k)} \qquad i = 1,\ldots,N_l \qquad (9)$$

$$G_{\min i} \le G_i^{(k)} \le G_{\max i} \qquad i = 1,\ldots,N_g \qquad (10)$$

$$P_{\max i}^{net(k)} \ge P_{\min i}^{(k)} \qquad i = 1,\ldots,N_l \qquad (11)$$

k denotes the kth iteration and $P_{\max i}^{net}$ is the optimum capacity of transmission line i for intact network

It should be noted that a chromosome may propose a network configuration for which no feasible solution can be found, for example physical laws (7) and (8) cannot be respected. In this case the fitness of the relevant chromosome is infinity.

When the GA converges to the optimum point, the best network topology of intact network is found along with the optimum generation pattern and transmission capacities. Due to limitations imposed by operating characters, power plants cannot change their output power rapidly hence the optimum generation pattern calculated in this stage should be kept unchanged for Stage-III.

C. Stage- III: Contingent Network

The optimum generation pattern calculated in Stage-II and the minimum required capacity proposed by Stage-I are inputs to this stage.

Unlike Stage-II, the objective function is to only minimize the transmission investment assuming that network reconfiguration is a possible action. The GA is again deployed to find the best network switching pattern. The fitness - $Fitness_{Stage-III}$ - of each chromosome proposing a switching pattern is the minimum transmission investment cost calculated by (7).

$$\underset{P_{\max i}^{c(k)}}{Minimize} \; : Fitness_{Stage-III} = \sum_{i=1, i \ne c}^{N_l} T_{mi}.l_i.P_{\max i}^{c(k)} \qquad (7)$$

Subject to:

$$\sum_{\forall i \in N_{gd}} G_i^{(k)} + \sum_{\forall i \in N_{ld}, i \ne c} P_i^{(k)} - L_d = 0 \qquad d = 1,\ldots,N_b \qquad (8)$$

$$P_i^{(k)} - \frac{\left(\theta_k^{(k)} - \theta_l^{(k)}\right)}{X_i} = 0 \qquad i = 1,\dots,N_l, i \neq c \quad (9)$$

$$-P_{\max i}^{c(k)} \leq P_i^{(k)} \leq P_{\max i}^{c(k)} \qquad i = 1,\dots,N_l, i \neq c \quad (10)$$

$$G_{\min i} \leq G_i^{(k)} \leq G_{\max i} \qquad i = 1,\dots,N_g \quad (11)$$

$$P_{\max i}^{c(k)} \geq P_{\min i}^{(k)} \qquad i = 1,\dots,N_l \quad (12)$$

In the above formulation, c represents a particular outage, $P_{\max i}^{c}$ is the optimum capacity of transmission line i if line c trips, and k denotes the k th iteration.

The outcomes of this stage are a list of optimum transmission capacities for every contingent network and its best network switching pattern to reach that optimum point.

D. Convergence condition

Stage I to Stage III are repeated until convergence criterion is satisfied. If for every single transmission line the average ($P_{avg_i}^{(k)}$) of all optimum capacities which are calculated in Stage II and Stage III is identical to the minimum required capacity (the byproduct of Stage I) then the convergence point has been reached. The iteration at which the convergence occurs, the minimum required capacities represent the optimum transmission capacities.

The average capacity for line i in iteration k can be formulated as follows:

$$P_{avgi}^{(k)} = \frac{\sum_{c=1}^{N_c} P_{\max i}^{c(k)} + P_{\max i}^{net(k)}}{N_c + 1} \qquad (13)$$

Where N_c is the number of contingent networks.

The whole process of the proposed method is shown in Fig. 3.

V. NUMERICAL STUDIES

The approach proposed for TNP is carried out on IEEE 24 bus network [10] details of which are given in Appendix A. This test system consists of 38 lines that all of them are considered as candidates for the final network. All credible contingencies are considered except the transmission line connecting Bus# 7 to Bus# 8, as outage of this line causes islanding in the network. All 24 substations in the test system are switchable.

In order to show the superiority of the flexible TNP over conventional TNP two different cases described below were undertaken.

Case1: Conventional TNP which has been described in section II.

Case2: Flexible TNP with network reconfiguration as proposed in this paper.

Also every step in the stepwise model for PTC is assumed to be 50 MW that can be mathematically expressed by (14), see Fig. 1.

$$\forall j : L_j - L_{j-1} = 50 \qquad (14)$$

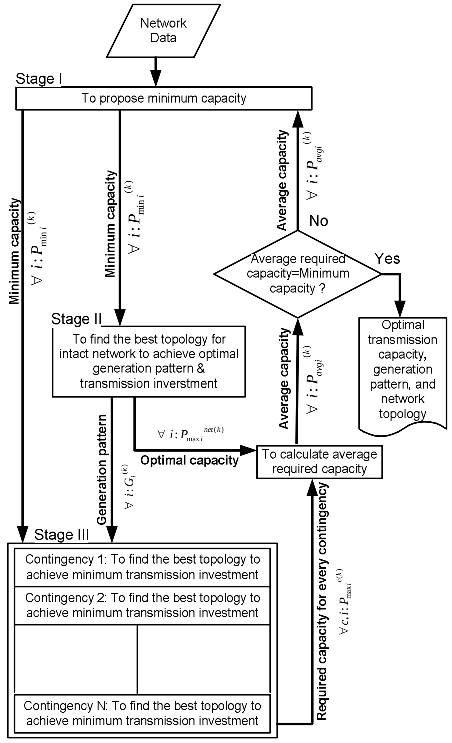

Fig. 3. Flexible TNP process under a network switching paradigm

As shown in Fig. 3 the optimum generation dispatches for both cases are identical, whereas the optimum transmission capacities which are depicted in Fig. 4 are completely different. Taking into account case1, all 38 lines have to be installed and a transmission investment of €2915640 should be made. In case 2, however, 6 out of 38 lines do not need to be constructed and the transmission investment is €2545920 which in contrast to case1 shows a 12.68% reduction in the cost. This considerable drop in investment has been achieved by deploying the network switching in TNP.

VI. CONCLUSION

A flexible transmission network planning approach which can be applied to future intelligent networks has been presented in this paper. Unlike the conventional TNP deploying preventive control, corrective post-contingency network switching action is proposed which enables the network to be reconfigured efficiently in contingency conditions. This new approach can find the optimum generation dispatch as well as optimum transmission capacity along with network switching pattern in all outage circumstances.

In order to take a practical approach to the problem a realistic model for a substation that is double bus-double breaker is assumed. Also, due to the lumpy nature of transmission investment, it has been modeled with a stepwise model.

The flexible TNP is a large scale optimization problem which has been solved by deploying a multi-stages iterative method. In each iteration the best network configurations have been found by deploying GA and some heuristic techniques.

The proposed method has been tested on IEEE 24 bus RTS test system and it has been compared with a conventional approach to TNP. The comparison showed a considerable reduction of 12.68% in transmission investment whereas no change in optimum generation pattern has been observed. In has been demonstrated that if flexible TNP is applied, 6 out of 38 lines would not be required significantly reducing the transmission expansion requirements.

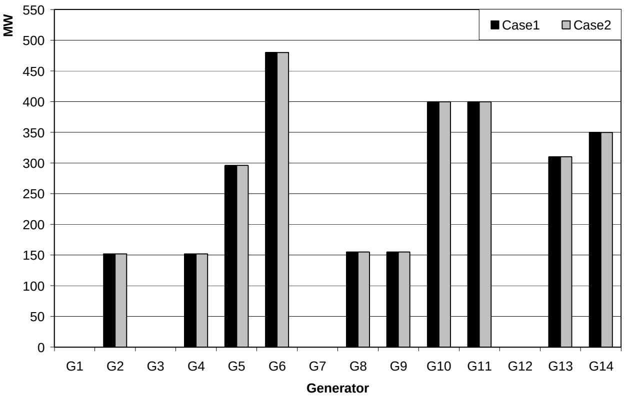

Fig. 4 Optimum generation dispatch in Case1 and Case2

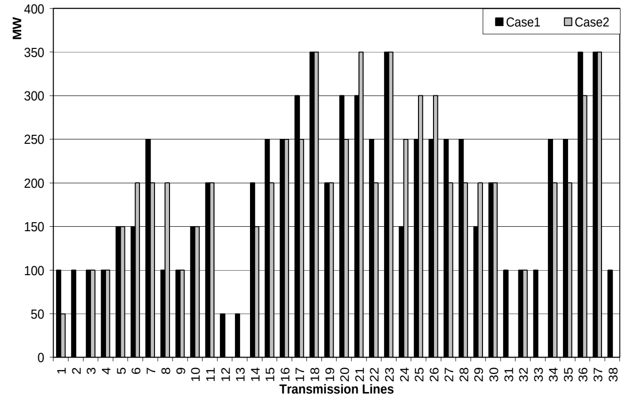

Fig. 5 Optimum transmission capacities in Case1 and Case2

APPENDIX A

The load demands at each bus are presented in Table A.I Table A.II shows the generation data. The annuitized transmission investment cost is assumed to be 11.7 €/Km.MW.Year which is based on National Grid report [11] and a currency exchange rate of £1.00= €1.23.

TABLE A.I
LOAD INFORMATION IN THE 24 BUS NETWORK

Bus #	Load (p.u.)	Bus #	Load (p.u.)	Bus #	Load (p.u.)
1	1.08	9	1.75	17	0
2	0.97	10	1.95	18	3.33
3	1.8	11	0	19	1.81
4	0.74	12	0	20	1.28
5	0.71	13	2.65	21	0
6	1.36	14	1.94	22	0
7	1.25	15	3.17	23	0
8	1.71	16	1	24	0

TABLE A.II
GENERATION INFORMATION IN THE 24 BUS NETWORK

Gen. #	Bus #	Gen. Type	Pmax (MW)	Pmin (MW)	€/MWh
G1	1	Wind	40	0	52.9
G2	1	Coal	152	0	45.2
G3	2	Wind	40	0	52.9
G4	2	Coal	152	0	45.2
G5	7	CCGT	300	0	51.2
G6	13	CCGT	591	0	51.2
G7	15	Wind	60	0	52.9
G8	15	Coal	155	0	45.2
G9	16	Coal	155	0	45.2
G10	18	Nuclear	400	0	35
G11	21	Nuclear	400	0	35
G12	22	CCGT	300	0	51.2
G13	23	Coal	310	0	45.2
G14	23	Coal	350	0	45.2

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