Controllable Transmission Networks with M-FACTS

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***Abstract*—The transmission system operators (TSOs) are responsible to provide secure and efficient access to the transmission system for all stakeholders. This task is gradually getting challenging due to the demand growth, demand uncertainty, rapid changes in generation mix, and market policies. Traditionally, the TSOs try to maximize the technical performance of the transmission network via building new overhead lines or physical hardening. However, obtaining public acceptance for building new lines is not an easy step in this procedure. For this reason, the TSOs try to capture the capabilities of existing assets. This paper investigates the use of modular FACTS devices (to alter the line characteristics) for improving the capability of transmission network in serving the uncertain demand without the need for building new overhead lines. The proposed OPF based method considers the uncertainty of demands and controls the utilization of existing transmission assets. The mathematical results obtained are validated with a complete non-linear simulation model of two transmission networks..**

***Index Terms*—Transmission network, Power flow controller, Congestion, Flexibility.**

NOMENCLATURE

The notations and symbols used throughout the paper are stated in this section.

Abbreviations:

MF	Membership Function
M-FACTS	Modular Flexible AC Transmission system
P2H	Power to hydrogen.
RES	Renewable Energy Sources
TSO	Transmission System Operator

Sets:

Ω_B	Set of network buses.
Ω_ℓ	Set of network lines.
Ω_G	Set of generating units.

Variables:

$\alpha^f(P)$	Forecasted membership function describing the uncertain demand
$\alpha^c(P)$	Calculated membership function describing the uncertain demand considering technical constraints
LR	Load repression
$P^\alpha_{i,D}$	Uncertain active demand at bus i.
$P^\alpha_{i,g}$	Uncertain active output of generator at bus i.
δ^α_i	Uncertain delta angle of bus i.

Parameters:

$\bar{\alpha}^{LR}_{min}$	Degree of load repression for load reduction
$\bar{\alpha}^{LR}_{max}$	Degree of load repression for load increase
$\beta^{min}_{i,j}$	Minimum flexibility of M-FATCS for changing the line impedance of the line connecting bus i to j.
$\beta^{max}_{i,j}$	Minimum flexibility of M-FATCS for changing the line impedance of the line connecting bus i to j.
$P^{min}_{i,g}$	Minimum operating limit of the generator connected to bus i.
$P^{max}_{i,g}$	Maximum operating limit of the generator connected to bus i.
$\bar{P}^\alpha_{i,D}$	Predicted active demand at bus i.
$\check{P}^\alpha_{i,D}$	Predicted lower bound active demand at bus i.
$\hat{P}^\alpha_{i,D}$	Predicted upper bound active demand at bus i.
$B_{i,j}$	Susceptance of the line connecting bus i to j.
$P^{lim}_{i,j}$	Thermal limit of line connecting bus i to j.
$\bar{\tau}$	Total available M-FACTS flexibility.
w_i	Weight factor indicating the importance of demand at bus i.

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I. INTRODUCTION

A. Motivations

THE role of transmission system operator is to keep the security and efficiency of the transmission network. The resilient transmission network should be able to deal with high impact low probability events [1]. The events can be named as natural disasters, cyber-attacks [2], physical attacks, simultaneous multiple component outages and etc. Another event that has the potential to cause cascading outages is transmission line overloading. In case, the throughput of a line is beyond the seasonal thermal limits then the protection system might cause an outage of this line and naturally the flow will be transferred to other parallel paths (if they exist). Another solution might be load shedding to alleviate the line's power flow. However, it is not a desirable or cheap solution for the customers. The adequacy of the transmission network in supplying the demand can be affected by different factors such as line impedance, thermal capacity, and network topology. Building new overhead lines (to address these problems) usually provokes the protest of residents mainly due to the land-use conflicts, noise, aesthetic concerns, and safety issues [3].

TSO should be able to efficiently use the existing assets to ensure the ability of the transmission system to meet reasonable demands [4], [5]. Some important factors should be taken in to account namely, the ideal solution should be rapidly applicable, capable of dealing with uncertainties [6], and finally, community acceptance. The Modular Flexible AC Transmission System (M-FACTS) devices can improve asset utilization and relieving the technical constraints by controlling the power flow in the transmission system [7]. The M-FACTS [8] are modular units that can be installed on some transmission lines and they are capable of pushing the power from heavily loaded lines to lightly loaded lines in the inductive mode of operation. In capacitive mode, the M-FACTS (installed on less loaded lines) will absorb the power from other lines. The M-FACTS devices have some advantages over the FACTS devices such as fast installation, redeployment possibility, and more flexibility for changing the line impedance [9].

B. Literature review

The M-FACTS have been studied in different power system contexts. For example,

- Resolving intact and post-contingency overloading [10]
- Phase current balancing [11] using the existing logistics infrastructure [12]
- Improving the sustainability of new designs and components installed on the grid [13]
- Transient stability improvement [14]
- Defending against False Data Injection Attacks [15]
- Reliability improvement of power system [16]
- Active loss minimization [17]

Some factors should be considered to decide about the optimal allocation of M-FACTS in transmission network such as:

- Mechanical strength of the line which is going to host the M-FACTS. The weight of the modular units should be tolerated by the cables and towers.
- There should be at least one parallel path to push/pull power to/from that path.
- The number of hours as well as the magnitude of risk that can be resolved using M-FACTS should be calculated. For example, if the impact of M-FACTS is reducing 1% of overload for a limited number of hours (out of 8760 hrs) then it might not be economically viable for investment.
- If there is more than one line equipped with M-FACTS then the coordination between their actions is the key element. The central or decentralized control of these devices should be carefully controlled [18].
- The M-FACTS need a minimum current to be able to operate. This is fine with reactive mode (which is helpful for heavily loaded lines) but it might cause problems in the capacitive mode of operation.
- The optimal allocation/operation of M-FACTS is highly dependant on the input assumptions and data of the problem. For example, demand profile, network configuration, RES generation, etc.

C. Contributions

The contributions of this work are twofold:

- Optimally allocate and operate M-FACTS devices in the transmission network
- Considering the net demand uncertainty using a fuzzy technique

D. Paper structure

The proposed methodology is described in section II. The simulation results are provided and discussed in section III. Finally, the paper is concluded in section IV.

II. Methodology

The objective is to maximize the abbot of the transmission network in supplying the demand even if the precise demand is unknown. There are several techniques to model the demand uncertainty such as scenario based modeling [19] and fuzzy methods [20]. The scenario based approach requires the probability density function of the uncertain parameter but the fuzzy approach can be utilised by expert opinion. In this work, the uncertainty of demand is described using a triangle fuzzy membership function (MF) [21] as shown in Fig. 1-a and mathematically described in (1a)-(1b) $\forall i \in \Omega_B$, the forcasted value of $\alpha^f(P)$ is described as:

$$P_{i,D}^{\alpha} \geq \bar{P}_{i,D} - (1-\alpha)(\bar{P}_{i,D} - \check{P}_{i,D}) \tag{1a}$$

$$P_{i,D}^{\alpha} \leq \bar{P}_{i,D} - (1-\alpha)(\bar{P}_{i,D} - \hat{P}_{i,D}) \tag{1b}$$

$\bar{P}_{i,D}, \hat{P}_{i,D}$ and $\check{P}_{i,D}$ in (1a), (1b) are the forecasted, upper and lower values for power demand at $\alpha = 0$, respectively. The demand should be able to reach these limits (at every α-cut) if the transmission network is fully adequate.

The concept of load repression (LR) was proposed in [22], which uses the α-cut technique [23] to specify the amount of demand that can not be served in a given bus. The total LR in the system is calculated by calculating the $\alpha^c(P)$ as follows:

$$\alpha^c(P) = \min / \max \sum_i w_i P_{i,D}^{\alpha} \tag{2a}$$

$$P_{i,g}^{\alpha} - P_{i,D}^{\alpha} = \sum_j (P_{i,j}^{\alpha}) \qquad \forall i \in \Omega_B \tag{2b}$$

$$P_{i,j}^{\alpha} = B_{i,j}(\delta_i^{\alpha} - \delta_j^{\alpha}) \qquad \forall ij \in \Omega_\ell \tag{2c}$$

$$-P_{i,j}^{lim} \leq P_{i,j}^{\alpha} \leq P_{i,j}^{lim} \qquad \forall ij \in \Omega_\ell \tag{2d}$$

$$P_{i,g}^{min} \leq P_{i,g}^{\alpha} \leq P_{i,g}^{max} \qquad \forall i \in \Omega_B, \forall g \in \Omega_G \tag{2e}$$

Constraint (1)

The weight factors (w_i) in (2a) show the importance of each demand. The nodal power balance is modeled in (2b).

Constraint (2c) indicates how line flow from bus i to bus j is calculated. Constraint (2d) specifies the line flow limits. Finally, constraint (2e) forces the generation limits. The severity of LR is shown in Fig.1-b (dotted area).

The degree of LR is the maximum value of α where LR does not happen. This quantity is depicted in Fig.1-b. The degree of load repression might be different for load reduction ($\bar{\alpha}_{min}^{LR}$) and load increase ($\bar{\alpha}_{max}^{LR}$). Fig.1-c indicates how LR is calculated at each α-level in maximization/minimization of demand for a given bus i. Fig.1-c also demonstrates why two separate optimization (min and max) are needed in (2).
Once (2) is solved then the total LR is calculated as follows:

$$LR = \int_{\check{P}_{i,D}}^{\hat{P}_{i,D}} (\alpha^f(P) - \alpha^c(P)) dP_{i,D} \quad (3)$$

$\alpha^f(P)$ and $\alpha^c(P)$ are the forecasted MF (1) and the calculated MF ((2) or (4)), respectively. By deploying a M-FACTS device in a given line, the line's reactance becomes a decision variable and may contribute to LR reduction if it is optimally determined. The mathematical formulation for LR calculation in presence of M-FACTS is as follows:

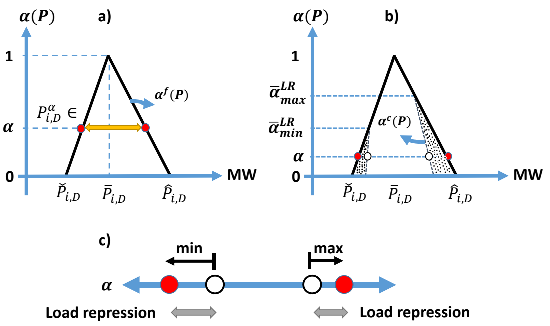

Fig. 1. The load repression concept

$$\alpha^c(P) = \min / \max \sum_i w_i P_{i,D}^{\alpha} \quad (4a)$$

$$P_{i,g}^{\alpha} - P_{i,D}^{\alpha} = \sum_j (P_{i,j}^{\alpha}) \qquad \forall i \in \Omega_B \quad (4b)$$

$$P_{i,j}^{\alpha} = (B_{i,j})(1+\beta_{i,j})(\delta_i^{\alpha} - \delta_j^{\alpha}) \qquad \forall ij \in \Omega_\ell \quad (4c)$$

$$\beta_{i,j}^{min} \le \beta_{i,j} \le \beta_{i,j}^{max} \qquad \forall ij \in \Omega_\ell \quad (4d)$$

$$-P_{i,j}^{lim} \le P_{i,j}^{\alpha} \le P_{i,j}^{lim} \qquad \forall ij \in \Omega_\ell \quad (4e)$$

$$P_{i,g}^{min} \le P_{i,g}^{\alpha} \le P_{i,g}^{max} \qquad \forall i \in \Omega_B, \forall g \in \Omega_G \quad (4f)$$

Constraint (1)

The value of $\beta_{i,j}$ in (4c) shows that how much change in the susceptance of the line between bus i and j ($B_{i,j}$) is going to happen. The reactance variation is limited to the characteristics of the M-FACTS device ($\beta_{i,j}^{min/max}$). If it is pure capacitive then $\beta_{i,j}^{min} = 0$ and $\beta_{i,j}^{max} \ge 0$.If it is pure inductive then $\beta_{i,j}^{min} \le 0$ and $\beta_{i,j}^{max} = 0$. The M-FACTS deployed on a specific transmission line can be operated in different modes based on the operating condition of the system.

In reality, the TSO has a limited amount of M-FACTS devices available so it is essential to know how to use them efficiently in case of a contingency. The following optimization answers this question:

$$\alpha^c(P) = \min / \max \sum_i w_i P_{i,D}^{\alpha} \quad (5a)$$

$$\sum_{i,j \in \Omega_\ell} |\beta_{i,j}| \le \bar{\tau} \quad (5b)$$

$$P_{i,g}^{\alpha} - P_{i,D}^{\alpha} = \sum_j (P_{i,j}^{\alpha}) \qquad \forall i \in \Omega_B \quad (5c)$$

$$P_{i,j}^{\alpha} = (B_{i,j})(1+\beta_{i,j})(\delta_i^{\alpha} - \delta_j^{\alpha}) \qquad \forall ij \in \Omega_\ell \quad (5d)$$

$$\beta_{i,j}^{min} \le \beta_{i,j} \le \beta_{i,j}^{max} \qquad \forall ij \in \Omega_\ell \quad (5e)$$

$$-P_{i,j}^{lim} \le P_{i,j}^{\alpha} \le P_{i,j}^{lim} \qquad \forall ij \in \Omega_\ell \quad (5f)$$

$$P_{i,g}^{min} \le P_{i,g}^{\alpha} \le P_{i,g}^{max} \qquad \forall i \in \Omega_B, \forall g \in \Omega_G \quad (5g)$$

Constraint (1)

where $\bar{\tau}$ is the total available M-FACTS flexibility in the system.

III. Simulation Results

The proposed framework in (4) and (5) are implemented in GAMS [24] and the non-linear problem is solved using KNITRO solver [25]. The simulations are implemented on two transmission networks namely 5-bus PJM network and IEEE 24 bus system.

A. Five bus system

The data of the system under study is shown in Fig. 2. The network characteristic data is provided in Table I.

TABLE I
LINE CHARACTERISTICS OF 5 BUS NETWORK

from bus	to bus	X (PU)	Limit (MW)
1	2	0.030	240
1	4	0.050	270
1	5	0.060	250
2	3	0.025	270
3	4	0.030	270
4	5	0.020	270

The forecasted values of demand ($\bar{P}_{i,D}$) are specified in Fig. 2. The upper and lower values of demand ($\hat{P}_{i,D}, \check{P}_{i,D}$) are assumed to be $\pm 5\%$ more/less than the forecasted values. The forecast error can be different from what is considered in this work but it does not change the general concept of the proposed framework. The LR calculation is done for four different strategies namely:

- Strategy c_1: Base case in which no M-FACTS device exists in the network $\beta_{i,j}^{min/max} = 0$. The network impedances are unchanged in this strategy.
- Strategy c_2: Inductive M-FACTS $\beta_{i,j}^{min} \le 0$, $\beta_{i,j}^{max} = 0$. In this case, the reactance increase is used for reducing the line loading.

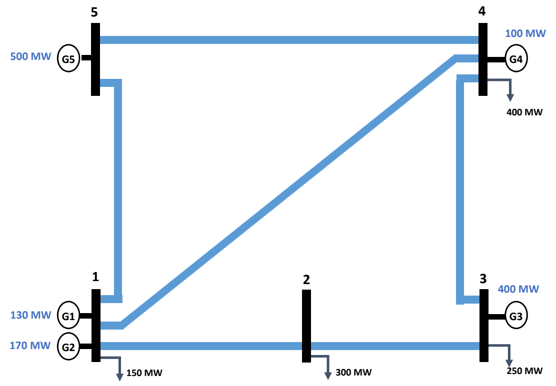

Fig. 2. Five bus network for explaining the repression concept

- Strategy c_3: Capacitive M-FACTS $\beta_{i,j}^{min} = 0$, $\beta_{i,j}^{max} \geq 0$. In this case, the reactance reduction is used for attracting flow from the heavily loaded lines.
- Strategy c_4: Smart (coordinated Inductive-Capacitive) M-FACTS are considered $\beta_{i,j}^{min} \leq 0$, $\beta_{i,j}^{max} \geq 0$. The reactance of some lines are increase while reducing the reactance on some other lines.

It is assumed that all lines are equipped with M-FACTS devices (c_{2-4}) and all w_i in (4) are equal. The M-FACTS capacity is assumed to be a percentage of the line's impedance. It is assumed that the actions of all M-FACTS are coordinated with each other. The load repression in all buses with demand are depicted for different control strategies in Fig.3.

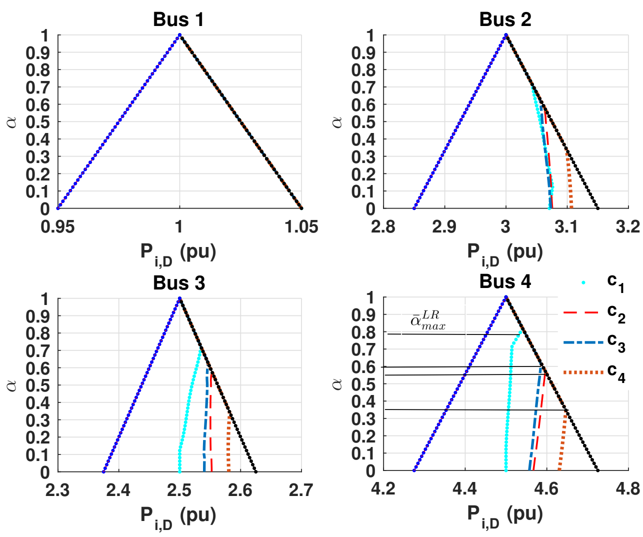

Fig. 3. The LR for c_1: Base, c_2: Inductive, c_3: Capacitive, c_4: Smart in five bus network case

The total LR is calculated using (3) and the results are given in table II. It can be observed that not only the total LR reduces in c_4 (compared to c_1) but also the degree of repression ($\bar{\alpha}_{max}^{LR}$) decreases. The optimal dispatch ($\beta_{i,j}$) decision for M-FACTS devices in different strategies are given in table III.

The capacity of M-FACTS devices are changed from 0 to 40% and the impact on total LR are shown in Fig. 4. The most effective strategy is inductive-capacitive coordination (c_4) for this system.

TABLE II
TOTAL LR FOR 5 BUS SYSTEM IN DIFFERENT STRATEGIES

Strategy	c_1	c_2	c_3	c_4
LR (MW)	17.427	8.926	10.396	3.255
$\bar{\alpha}_{i=1,max}^{LR}$	0	0	0	0
$\bar{\alpha}_{i=2,max}^{LR}$	0.70	0.57	0.62	0.33
$\bar{\alpha}_{i=3,max}^{LR}$	0.70	0.58	0.61	0.32
$\bar{\alpha}_{i=4,max}^{LR}$	0.80	0.55	0.60	0.35

TABLE III
M-FACTS DISPATCH ($\beta_{i,j}$) FOR 5 BUS SYSTEM IN DIFFERENT STRATEGIES

FACTS location $(i-j)$	c_2	c_3	c_4
2-1	-0.1499	0.0520	-0.0965
4-1		0.2000	0.2000
5-1		0.2000	0.2000
3-2	-0.0760	0.1196	0.1171
4-3	-0.1057	0.1054	-0.0561
5-4	-0.2000		-0.2000

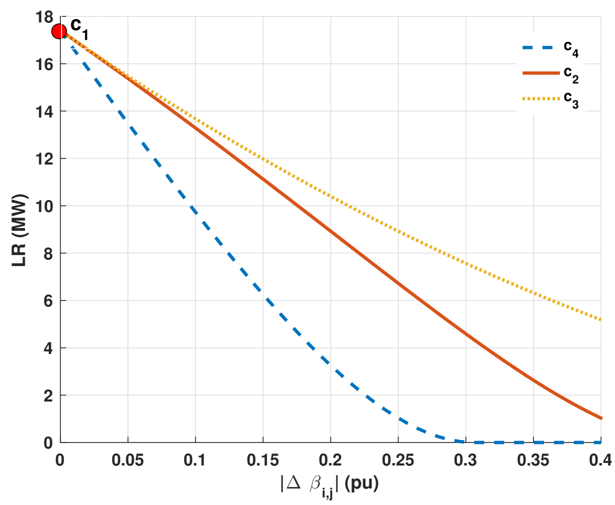

Fig. 4. Impact of M-FACTS capacity on load repression of 5 bus network in different strategies: Sensitivity analysis; c_2: Inductive , c_3: Capacitive , c_4: Smart

B. IEEE 24 bus system

The single line diagram of IEEE 24 bus system is depicted in Fig. 5. The data of this system is available in [26]. In this case, it is assumed that $\check{P}_{i,D} = 0.9\bar{P}_{i,D}$ and $\hat{P}_{i,D} = 1.1\bar{P}_{i,D}$. This system does not show any load repression in the intact condition. Now, the impact of all single-line outages on LR are investigated and the results are shown in Fig. 6. Similar to the previous case, the capacity of M-FACTS devices are changed from 0 to 40% and the impact on total LR are shown in Fig. 4 and the line contingencies with $LR \geq 0$ are plotted. As it can be observed in this figure, the most effective strategy is inductive-capacitive coordination (c_4) for this system.

It is important to know which buses are contributing to the LR when a contingency happens. The impacts of different contingencies on the load repression vs M-FACTS capacity are

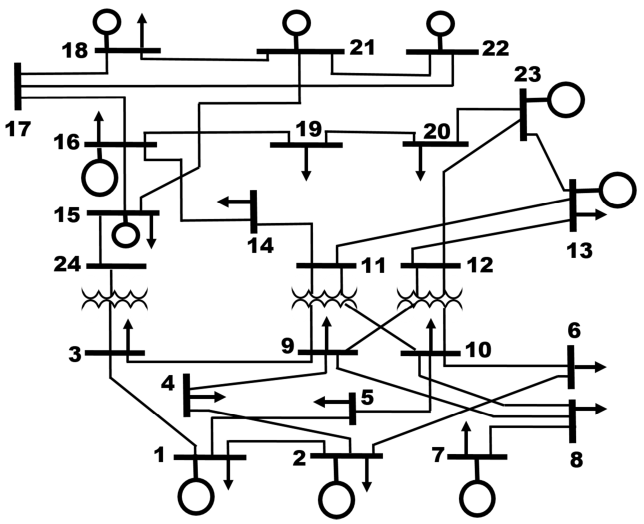

Fig. 5. Single line diagram of IEEE 24 bus system

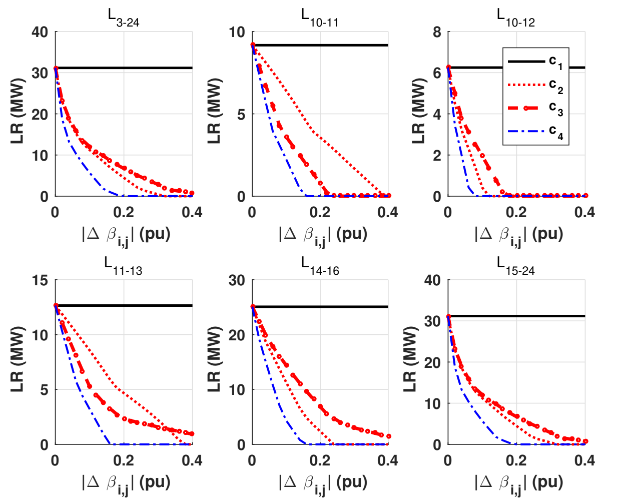

Fig. 6. Impact of M-FACTS capacity and line contingencies on the load repression of IEEE 24 bus network in different strategies: Sensitivity analysis; c_2: Inductive, c_3: Capacitive, c_4: Smart

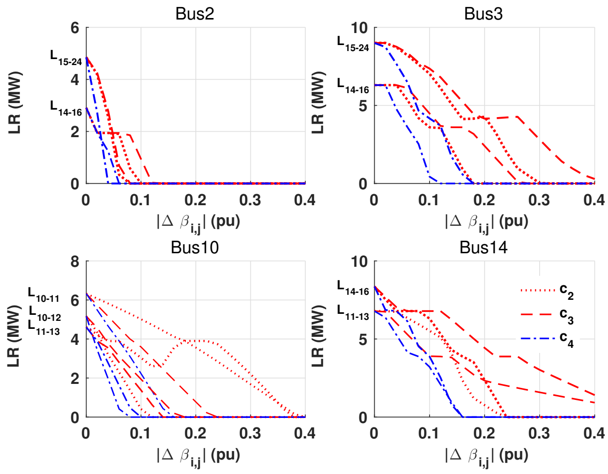

Fig. 7. Impact of contingencies and M-FACTS capacity on load repression of different buses in each strategy; c_2: Inductive , c_3: Capacitive , c_4: Smart in IEEE 24 bus system

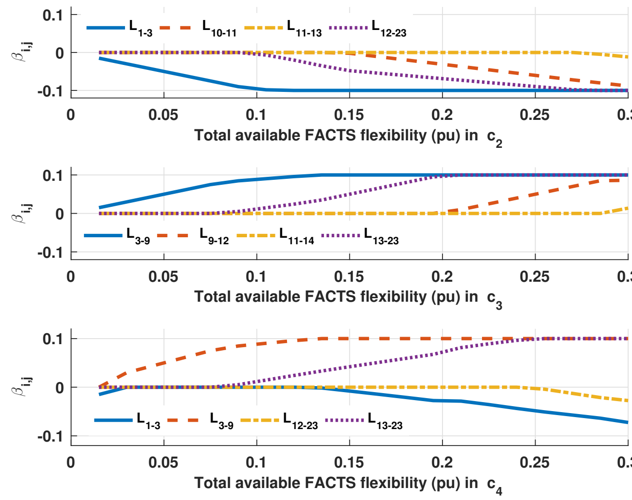

Fig. 8. The optimal M-FACTS deployment vs available M-FACTS flexibility in each strategy when L_{15-24} is out of service in IEEE 24 bus system

shown in Fig. 7. As it is expected, the location of the bus, the amount of load on that bus, and also the contingency affect the LR in each strategy. For example, on bus 3, the LR is 8.99 MW when the line connecting bus 15-24 is out of service. With the increase of M-FACTS capacity, this LR reduces in all strategies ($c_{2,3,4}$). Obviously, the most efficient way of dealing with LR is c_4 strategy in which, the LR becomes zero at $|\beta_{i,j}| = 0.18$ pu. The optimal M-FACT deployment/exploitation vs the $\bar{\tau}$ (5) is plotted in Fig.8 in different strategies. This graph shows how TSO should react against the L_{15-24} outage in different strategies. For example, in pure inductive M-FACTS (c_2), the order of activating the M-FACTS is $L_{1-3} \rightarrow L_{12-23} \rightarrow L_{10-11} \rightarrow L_{11-13}$.

IV. Conclusion

The proposed method can provide useful indicators to TSO in effectively dispatching the transmission network using M-FACTS. The main findings of this paper are outlined as follows:

- The optimal operating settings of M-FACTS are necessarily real-time or on hourly-basis. The seasonal settings seems to be more practical. The modularity of M-FACTS allows them to be redeployed with a short lead time if needed.
- The deployment line of M-FACTS as well as the size of it have significant impacts on the control-ability of the transmission network. This is due to the physical rules behind the OPF equations. It is important to optimally determine the capacity as well as the location of them otherwise, the anticipated flexibility will not be achieved.
- The optimal deployment strategy will remain valid as far as the network configuration does not change. If it is

changed because of maintenance or contingencies then the flexibility of the configured M-FACTs is affected.

- The presence of uncertain renewable power generation can increase the uncertainty of the net load at each given bus. This has the potential to increase the load repression and M-FACTS can be helpful to reduce it.
- The M-FACTS is considered as a non-wire solution since it does not require building a new overhead line. However, if the planning of M-FACTS as well as the traditional overhead lines [27] are done simultaneously then a higher level of control will be achieved.

Suggestions for future work:

- The impact of flexible transmission network on unit commitment formulation should be investigated.
- A more detailed multi-period AC-OPF can better characterize the impact of M-FACTS on transmission systems.
- The impact of M-FATCS on voltage stability should be investigated. Altering the line impedance will change the load-ability margin of a given system. This should be taken into account to avoid technical problems for the system hosting M-FACTS.
- The uncertainty of wind power generation should be taken into account to avoid financial and technical risks [28].
- The risk of cyber attacks on M-FACTS should be investigated. The attackers may endanger the security of the power system by sending false commands to these devices and cause cascading failures.
- It should be noted that if the power flow is pushed from a heavily loaded line to less loaded line the destination line also remains in safe operating condition.
- Cost-benefit analysis can justify the optimal investment decisions for the TSO.

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