Mitigation of Distributed Controller Failure

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Abstract— **While power flow between buses cannot be directly controlled, the use of Flexible AC Transmission systems allow a reasonable degree of control of power flow in the lines through changes in the effective impedance of the line. In cases of failure of Distributed FACTS [1], where they fail to inject the reactive power that is expected, the lines can be overloaded or have flows that create unstable bus voltages. This paper proposes an algorithm to modify the settings of the other D-FACTS controllers in the system to achieve stable operation, given the failure of one or more distributed controller (malicious or benign). This paper presents results for corrective operation settings for D-FACTS controller that can be extended to other FACTS.**

Keywords— Distributed Control, D-FACTS, Failure Mitigation

I. INTRODUCTION

The use of FACT devices on transmission lines to control power flow between buses improves the cost-effectiveness and reliability of the grid's operation. The purpose of this paper is to employ operational FACT devices in the system to mitigate the effects of failure of another FACT device. While a single line may have multiple devices installed, the modeling for the purposes of this paper is done in bulk. This paper considers D-FACT devices, as discussed in [1], [2], [3], but, the technique presented is generic in nature. The compensation of failure in transmission systems can be critical, and in cases where a controller in a near-overloaded system fails, it could lead to cascading failures or blackouts [4]. This paper proposes a methodology to mitigate the effect of a dysfunctional controller ('Dysfunctional' and 'failure' is defined for the purposes of this paper as a FACTs controller that does not operate, that is, injects zero reactive power into the line) through analysis of the effect of other controllers in the system on the concerned line and determining corrective actions while accounting for stable range of bus voltages and angles of the system.

A motivating factor to implement such mitigation methods to compensate for controller failure is system operations. A failure of a FACT device would result in an increase in line current, which could be picked up by a protective relay. While this need not necessarily result in the tripping of breakers, it is an undesired event.

The paper is divided into nine sections. Section II provides a brief overview of the literature cited by the paper and how existing techniques is adapted for the objective of the paper. Section III summarizes the methodology used and the explanation of the methodology is contained in sections IV and V. Two test cases are presented in the following two sections and the results and discussion are included in section VIII. A conclusion of the work highlighting its significances is presented in the final section.

TABLE I: NOMENCLATURE

n	Number of buses
m	Number of lines
M	Number of controllers ($M \leq m$)
c	Number of controllers that have failed
z	Number of controllers in the identified support group
V_i	Voltage at bus iI'
θ_i	Voltage angle at bus 'i'
$S_i=P_i + jQ_i$	Complex power at bus 'i'
$S_{gi} = P_{gi} + jQ_{gi}$	Complex power injection at bus 'i'
$S_{li} = P_{li} + jQ_{li}$	Complex power consumption at bus 'i'
$Ybus = G + jB$	Admittance matrix of the system
	Subscripts
i,j	Bus indices ($0 \leq i, j \leq n$)

II. LITERATURE REVIEW

In this section, the implementation of the controller clustering and coupling indices elucidated in [5], [6] for the algorithm are explained. The sensitivity matrix (Of dimensions mxm for an 'n' bus, 'm' system) of a power system is defined as the partial derivative of the power flows to line impedances. The coupling index for power transmission systems is defined as the cosine of the angle between two row vectors $\boldsymbol{\partial P_i}, \boldsymbol{\partial P_j}$ of the sensitivity matrix. Mathematically,

$$\mathrm{C.I.(i,j)} = \cos\theta_{i,j} = \frac{\boldsymbol{\partial P_i}.\boldsymbol{\partial P_j}}{|\,\boldsymbol{\partial P_i}\,|.|\boldsymbol{\partial P_j}|} \tag{1}$$

For determining the effective compensating controllers, the coupling indices of all line pairs are computed using equation (1) and clustered to form controller groups. Each group contains a set of controllers which influence each other. The use of controller groups in the algorithm is explained in section III.

For conventional procedures in control system design, while decoupling is desired and negative coupling index (Which is reflective of a negative relative gain) is traditionally avoided, the proposed algorithm operates under coupled conditions and does not seek to filter out the effect of elements (controllers on

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other lines) with negative coupling indices. It operates thus for two reasons, a) To take advantage of the coupled nature of the system to influence lines with controllers that have failed, and b) A negative relative gain corresponds to a negative change in the effective line impedance, thus scaling a controller output's multiplicative factor in the range of [-1, 0) to a negative additive factor in the physical parameter, that is, to utilize the negative coupling wherein line flows are negatively coupled with respect to impedance; increasing the flow on one line (with a Δ change in the D-FACTS settings) will decrease the flow on the other line (With a Δ' change in D-FACTS settings).

III. SOLUTION OVERVIEW

The proposed methodology computes the maximum corrective action that can be made by other FACT devices in the system through online computations. A reference list of effective controllers that can compensate for the failure of the controller in focus is created and used as reference data for the algorithm to make computations.

The computations determine the change in the effective line impedance that is required from the compensating controllers to mitigate the failure. Based on the type of FACT device, the p.u. change in impedance can be converted to a proportional control signal that triggers the device to make the corresponding reactive injections into the line.

The proposed method detects the failure of the controller and based on the location of the controller and prior knowledge of the coupling effect of other controllers on the dysfunctional controller's line, selects a set of functional controllers and performs computations based on the proposed algorithm to compensate for the increase in line current due to the controller failure.

IV. ALGORITHM DATA PREPROCESSING

The proposed Distributed Failure Mitigation algorithm (Henceforth, referred to as the DFM algorithm) performs online calculations based on the knowledge of the system, namely, its topology, the last available data of load and generation distribution and knowledge of controller support groups that are determined as discussed in the previous section. The terminology 'Controller support group' is used to indicate the group of controllers that are selected to perform corrective mitigation steps. The selection of controller support groups is done via offline analysis, as seen in [6].

Failure of a controller is determined by periodic estimation of the line impedance using the reactive power flowing through the line and comparing the estimated value with the results of the line impedance estimated using the operating state of the controller. A large discrepancy in these values would imply that the controller is dysfunctional.

In order to determine a new operating state for the controllers, the algorithm reads the available PMU data (if any) to perform state estimation. In conditions where PMU data are unavailable, the state estimation results performed by the Energy Management System are used. If the controller failure has caused a large deviation of bus voltages from the tolerable voltage range, computations are based by setting the bus voltage to the tolerance limit.

The overall procedure is summarized using the flowchart in figure 1.

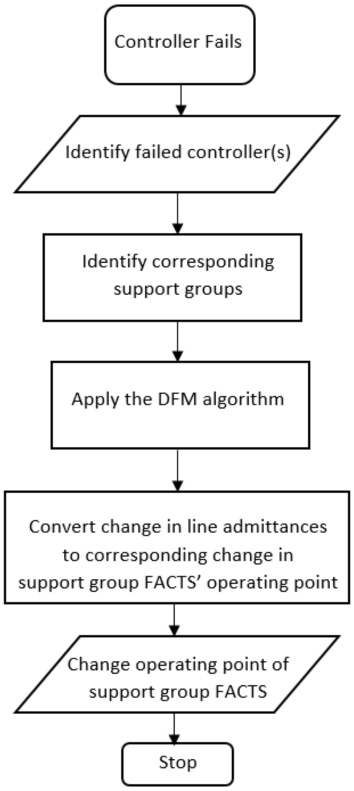

Fig. 1: Flowchart summarizing the mitigation technique used.

The algorithm computes the change in effective line impedance(s) required using the AC Power Flow equations and Newton-Raphson iterative method to solve them.

The real and reactive power consumed at each bus 'i', is expressed as:

$$P_i = P_{Gi} - P_{li} = |V_i| \sum_{j=1, j\neq i}^{n} |V_j| (G_{ij} \cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{2}$$

$$Q_i = Q_{Gi} - Q_{li} = |V_i| \sum_{j=1, j\neq i}^{n} |V_j| (-B_{ij} \cos\theta_{ij} + G_{ij} sin\theta_{ij}) \tag{3}$$

Considering that the conductance of lines (G) is usually far smaller than its susceptance (B), G is ignored. Additionally, since the results of this algorithm are susceptive quantities computed by using partial derivatives, even a significant value of conductance does not considerably affect the final results. Using this assumption, the equations are reduced to:

$$P_i = P_{Gi} - P_{li} \sim |V_i| \sum_{j=1, j\neq i}^{n} |V_j| (B_{ij} sin\theta_{ij}) \qquad (4)$$
$$Q_i = Q_{li} - Q_{Gi} \sim |V_i| \sum_{j=1, j\neq i}^{n} |V_j| (B_{ij} \cos\theta_{ij}) \qquad (5)$$

The resultant equations are differentiated partially with reference to the line susceptance for all lines with FACTS devices, line$_{i,j}$ (j =1 to n, j ≠ i) to obtain partial derivatives of the power flows with respect to effective line susceptance. Equation 6 is reflective of the direct sensitivity elements of the sensitivity matrix described in the previous section.

$$\frac{\partial P_i}{\partial B_{ij}} = |V_i||V_j| \sin\theta_{ij} \qquad (6)$$

$$\frac{\partial Q_i}{\partial B_{ij}} = |V_i||V_j| \cos\theta_{ij} \qquad (7)$$

From the above equations, it is observed that under an ideal condition (All bus voltages are $1\angle 0^{o}$, irrespective of complex power generated and consumed), the partial derivatives of real power tend to zero and the partial derivatives of reactive power tend to unity (As expected, since susceptance, being an imaginary quantity should not affect real power consumption or real power loss). Thus, for non-ideal cases, the following conditions (Equations 8. and 9.) are used as an approximation that must be satisfied for convergence in corrective calculations.

$$\frac{\partial P_i}{\partial B_{ij}} \sim 0 \qquad (8)$$

$$\frac{\partial Q_i}{\partial B_{ij}} \sim 1 \qquad (9)$$

Based on the equations (8) and (9), the algorithm computes the change in susceptance using the partial derivatives of reactive power and the computed values are validated using the partial derivatives of real power. This convention is chosen so that the matrix formed as a result of the above computations is not singular. A matrix consisting of only the partial derivatives of reactive power will have elements that are both unity and zero, thus not being singular. While interconnecting all buses with each other would cause this matrix to be singular, such a configuration is highly impractical for larger systems and hence, the matrix formed is treated as always invertible. One corrective computation (That is, a non-iterative computation scheme) is made for each coupled controller based on the clustering results. As a generalized rule, for a system with ‘n’ buses, ‘m’ lines, ‘M’ controllers (M ≤ m) and ‘c’ failed controllers, computations are performed using less than ‘m – c’ partial derivative equations and can use a minimum of ‘m – M + c’ partial derivative equations for validation.

A controller with strong coupling to all other controllers would require the maximum number of computations, that is, (m – c) computations. The usage of equations is summarized in Table II.

TABLE II: SUMMARY OF NUMBER OF PARTIAL DERIVATIVES USED

Equations Available	**Number of control computations required**	**Equations available for validation**
2m	≤ m - c	≥ m - M + c

V. THE DFM ALGORITHM

The detection of controller failure can be performed using estimation techniques and one of the possible estimation techniques has been briefly states in Section I. Assuming that the dysfunctional controller has been detected, the DFM technique operates using the following steps:

1. Identify location of failed controller(s).
2. Check if any thermal limits or bus voltage limits have been violated due to the failure. If not, go to step 16.
3. Set the admittance values of lines with dysfunctional controllers to their standard, zero injection values, that is, assume the controllers are turned off.
4. Identify the support group controllers and form a column vector **B`**, which has the present values of line susceptance.
5. If one of the supporting controllers has failed, eliminate it from **B`**.
6. If a controller appears in multiple support groups, eliminate its redundant inclusions in **B`**. Let z= size of **B`**.
7. For computation purposes, assign any unstable values of bus voltages and angles to the nearest stable and acceptable value.
8. Compute $\frac{\partial Q_i}{\partial B_{ij}}$ (i = 1, 2 … n, i≠j) ∀ B_{ij} ∈ **B`**.
9. If ‘z’ > ‘m’, Compute $\frac{\partial P_i}{\partial B_{ij}}$ (i = 1, 2 … n, i≠j) until number of real power computations = z – m.
10. Form matrix **J** = $[\frac{\partial Q_1}{\partial B_{i1j}}\ \frac{\partial Q_1}{\partial B_{i2j}}\ \ldots;\ \frac{\partial Q_2}{\partial B_{i1j}}\ \frac{\partial Q_2}{\partial B_{i2j}}\ \ldots;]$ of dimensions z x z using the computed values of $\frac{\partial Q_i}{\partial B_{ij}}$, $\frac{\partial P_i}{\partial B_{ij}}$ ∀ B_{ij} ∈ **B`**.
11. Form matrix **F** = $[Q_1\ Q_2\ Q_3\ \ldots.\ Q_n\ P_1\ P_2\ P_3 \ldots\ P_n]^T$ of dimension ‘z’x1 using available data on power demand and generation.
12. Compute Δ**B** = -**J**$^{-1}$**F** and update corresponding Y_{Bus} matrix.
13. If any susceptance limits in **Y**$_{Bus}$ are exceeded, saturate the value at the limit.
14. Verify the new **Y**$_{Bus}$ by computing new bus voltages and checking if the partial derivative equations reserved for model validation are satisfied.
15. If new bus voltages exceed limits and the controller isn’t critical to the system, go to step 8. If not, go to step 17.
16. Indicate that the failure does not require any corrective actions.
17. Stop

In the above algorithm, step 14 acts as a rudimentary check to verify the convergence of power-flow equations of the system. For instances where the algorithm is run for multiple iterations, this is followed at the end by checking for convergence using power flow equations. In instances of where the algorithm is executed for only one iteration, this step can be replaced by implementing AC Power-Flow or OPF to verify the results.

Figure 2 represents the goal of the algorithm graphically. For a case of controller failure that causes the line current to increase from 0.446 p.u. to 0.56 p.u., the algorithm re-sets the settings of other controllers to bring it as close of 0.446 p.u. as possible. The horizontal lines in the figure mark the point where the controller failure is detected, the point where the mitigation scheme is applied and the deviation from desired value after mitigation respectively. The transient response shown in the image is representative and not an exact plot.

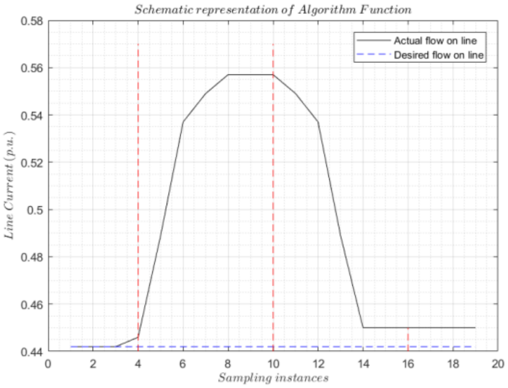

Fig. 2: Schematic graphical representation of the increase in line current due to controller failure and its subsequent decrease after mitigation is applied.

The preprocessing of data explained in the previous section is implemented in steps (1 – 8) of the algorithm. The methodology uses a single iteration Newton-Raphson method to compute the change in susceptance that is required by supportive controllers to maintain system voltage and bus angles within tolerable limits. As proposed in [6], controllers are either classified as critical, essential and redundant. Since complete control of system cannot be achieved with the failure of a critical controller, the DFM algorithm does not make multiple iterations to re-compute a possible combination of controller settings that will satisfy all limits and system conditions. In such cases, a solution that satisfies majority of the convergence criterion are selected as the final results.

The matrix 'J' is the Jacobian matrix that is used to compute the change in line susceptances that are required. It is formed using equations 6. and 7.; this is similar to the Jacobian matrix formed for power flow calculations to estimate the bus voltages. However, the derivatives used in the latter are with respect to bus angle and voltage, while the proposed method uses derivatives with respect to susceptance. Based on the computed value of J, the calculated matrices are substituted in the formula for multivariable Newton-Raphson iterative solution (Equation 10) and the change in solution is calculated.

$$\boldsymbol{x}^{(v+1)} = \boldsymbol{x}^{v} - F(\boldsymbol{x})'^{-1}.F(\boldsymbol{x}) \qquad (10)$$

For scenarios where multiple iterations of corrective computations are implemented, the convergence criterion for the algorithm is set to satisfy both the following relationships:

$$|\, V_i - 1.0 \,| \leq 0.05\, p.u.\ \forall\, i \qquad (11)$$

$$\left|\frac{\partial P_i}{\partial B_{ij}}\right| \leq \epsilon, \forall\, i, j \qquad (12)$$

$$I_{Line\,(i,j)} < I_{Line\,(i,j)}^{Limit},\ \forall\,(i,j) \qquad (13)$$

In the above convergence criterions, the parameter ϵ is a small value that tends to zero. Additionally, the tolerance limit for equation (11) can be varied as per the PV curve of the system or the operating standards implemented.

The bus angles are implicitly accounted for in equation (12). The above methodology was applied to a 7 Bus system and the results were analyzed.

VI. APPLICATION: 7 BUS, 11 LINE, 3 CONTROLLER SYSTEM

The DFM algorithm was tested on a 7 Bus system in PowerWorld using the software's demo case [8], shown in figure 3. The 7 bus system is divided into 3 areas with 11 transmission lines, 2 of which run parallel from bus 6 to 7. Although there are no FACT Devices installed on the lines, the algorithm would consider the equivalent effective impedance by both lines in computations. In such a case (As described in section VII), the overall susceptance change required by the lines is computed by the algorithm and another topology sensitive algorithm needs to be added to obtain the individual changes required.

The present case has D-FACTs installed in lines 1-2, 1-3 and 2-5. The devices are current sensitive, active when line current is between 75% and 100% of rated limit. They vary the effective admittance of the lines up to 30% of the base value, which correspond to j5.94, j1.2413 and j2.4827 respectively. The algorithm is applied to a situation in which the controller from bus 2 – bus 5 fails. The algorithm is tested for two conditions:

1) The controller fails, but at a juncture where no injection is required. (Figure 3)
2) The controller is in operation (As seen in Figure 4), but becomes dysfunctional suddenly, that is, injects 0.0 pu of susceptance.

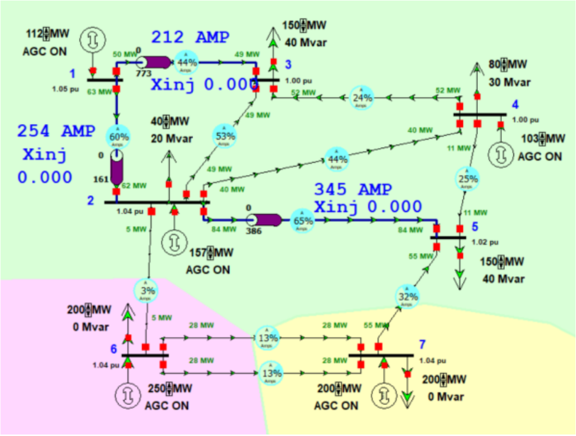

Fig. 3: Test system in *PowerWorld* for conditions under zero injection.

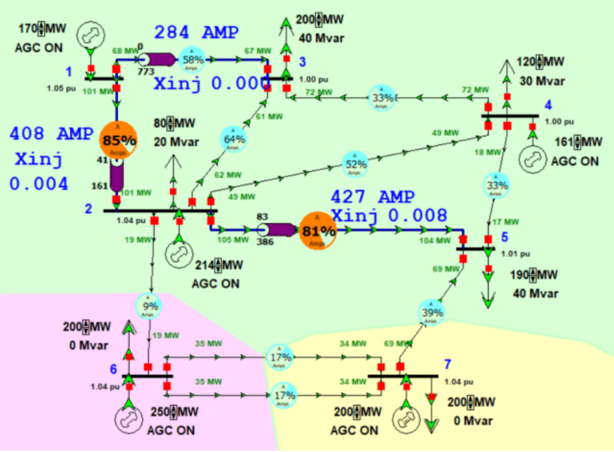

Fig. 4: Test system in *PowerWorld* for conditions under non–zero injection.

The sum squared error is computed considering the bus voltage magnitudes and ignoring the angles. It is computed as follows:

$$E = \frac{\sum (V_{act}-1.0)^2}{n} \qquad (14)$$

The results are presented in the following tables for the above scenarios. The results have been computed with a single iteration of Newton-Raphson solution. The 'limits' referred to in the tables are the maximum change in line susceptance that can be achieved by a FACT device. In situations where the computed correction value is greater than the maximum achievable limit, the correction value is set to the achievable limit.

The 'suggested ΔB' parameters referred to in the tables is the change in line susceptance required to compensate for the failure of controller(s) under scrutiny. This is a generic quantity that can be used to compute the new settings of a FACTS device based on its operation principle. While this paper presents all the results for Distributed FACTS, as noted previously, these parameters can be used to compute the settings of any generic FACTs device by converting the values of ΔB to change in line impedance and computing the operating point of the device that would cause such a change in the line impedance.

TABLE III: Results of controller 2-5 failure with 0.0 injection

Algorithm Suggested ΔB_{12}	**Algorithm Suggested ΔB_{13}**	**Sum Squared Error of Bus Voltages**
j0.093	-j0.03	0.0015

TABLE IV: Results of Controller 2-5 failure at non-zero injection

Algorithm Suggested ΔB_{12}	**Algorithm Suggested ΔB_{13}**	**Sum Squared Error of Bus Voltages**
j0.1677	-j0.124	0.0025

TABLE V: Results of Controller 2-5 failure at non-zero injection after considering limits

Algorithm Suggested ΔB_{12}	**Algorithm Suggested ΔB_{13}**	**Sum Squared Error of Bus Voltages**
j0.0168	-j0.0459	0.003

The algorithm is implemented for failure of controller 2-5 (Identified as a critical controller to the system) and the results are shown in tables III – V. A non-critical controller on line 1-2 is also analyzed and the results are indicated in tables VI and VII.

TABLE VI: Results of controller 1-2 failure with 0.0 injection

Algorithm Suggested ΔB_{13}	**Algorithm Suggested ΔB_{25}**	**Sum Squared Error of Bus Voltages**
j0.063	j0.096	0.0012

TABLE VII: Results of controller 1-2 failure at non-zero injection

Algorithm Suggested ΔB_{13}	**Algorithm Suggested ΔB_{25}**	**Sum Squared Error of Bus Voltages**
j0.0459	j0.1767	0.0021

VII. APPLICATION: 7 BUS, 11 LINE, 11 CONTROLLER SYSTEM

Although controllers on all lines are impractical and superfluous, this case is considered as it contrasts the fundamental scenario seen in the previous section, where there are more equations for validation than the ones required for computation. This condition requires the maximum number of corrective actions (Up to 10, for a single controller) to be computed and offers the minimal number of equations (3) to validate the model.

In the case of failure at non-zero injection condition, it is observed that the required change in operating points of the other controllers in the same cluster group exceeds the maximum possible change in operating point of the controller.

TABLE VII: Results of non-limited controller failure at non-zero injection

Algorithm Suggested ΔB_{13}	**Algorithm Suggested ΔB_{23}**	**Algorithm Suggested ΔB_{34}**	**Algorithm Suggested ΔB_{45}**	**Sum Squared Error of Bus Voltages**
j0.0459	j0.1769	-j0.6232	-j0.36$_{52}$	0.0032

TABLE IX: Results of limited controller failure at non-zero injection

Algorithm Suggested ΔB_{13}	**Algorithm Suggested ΔB_{23}**	**Algorithm Suggested ΔB_{34}**	**Algorithm Suggested ΔB_{45}**	**Sum Squared Error of Bus Voltages**
j0.0459	j0.0604	-j0.2412	-j0.08055	0.024

VIII. RESULTS AND DISCUSSION

Equations (11) and (12) provide one of the many possible convergence criterion that can be applied. They are chosen for the purposes of this paper to reflect the fundamental operating principle of the DFM algorithm and can be extended to account for various other aspects of the system. Some of the other convergence criterion that can be implemented include checking for convergence of power flow equations, accounting for economic constraints etc.

In the test case selected in section VI and VII, the direct and indirect correlation between the lines is noted by the negative and positive magnitudes is found to be consistent. That is, when a controller's effective mitigation is found to be negative for the zero injection case, it is also found to be negative for a non-zero injection case. This corresponds to the nature direct or reverse acting nature of the coupling indices of the line.

For both the test cases, the algorithm suggests a remedial change in the operating points of the other controllers even when the controller in concern does no inject any reactance into the line. In condition (1) of section VI, the results expected were a zero magnitude change required from the susceptances of the other two controllers. However, a minor change was noticed. This could be the result of two successive stages of approximation involved at (a) estimating the bus voltages and (b) the single iteration of Newton-Raphson convergence method used in the DFM algorithm.

Tables X and XI illustrates the maximum deviation of bus voltage from nominal voltage before and after mitigation. It can be seen that there is no significant gain obtained by using iterative calculations to determine the settings of the other controllers.

TABLE X: Maximum Bus Voltage deviations from 1.0 p.u.for 3 controller case

Scenario	**Maximum Deviation (p.u.)**	**Sum Squared Error of Bus Voltages**
Before mitigation	0.05	-
After running DFM for 1 iteration	0.0252	0.0021
After running DFM for 3 iterations	0.0252	0.0021

TABLE XI: Maximum Bus Voltage deviations from 1.0 p.u.for 11 controller case

Scenario	**Maximum Deviation (p.u.)**	**Sum Squared Error of Bus Voltages**
Before mitigation	0.05	-
After running DFM for 1 iteration	0.0232	0.024
After running DFM for 3 iterations	0.0253	0.022

For the system described in section VI, the magnitude of bus voltages before and after the mitigation are shown in figure 5 while figure 6 presents the bus voltage results for the system described in section VII. It is observed that the magnitude of bus voltages are closer to the nominal value (1.0 p.u.) in both cases after the DFM algorithm is applied.

In the following results, it can be seen that the bus voltages do not improve with multiple iterations of the DFM algorithm. Thus, it can be concluded that it can be used non-iteratively for small systems to provide effective mitigation. This conclusion is further supported by the plot of bus voltages for the 11 controller system. Although there exists a relatively greater difference in bus voltages between iterations (when compared to the 3 controller case), on absolute terms, the difference is negligible.

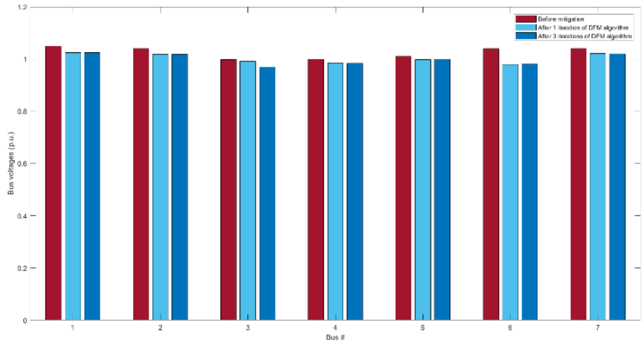

Fig. 5: Bus voltages before and after mitigation for the 3 controller system.

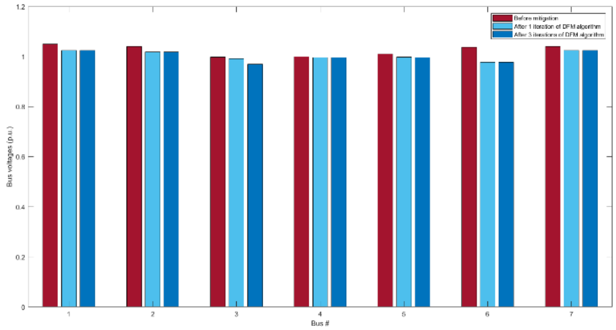

Fig. 6: Bus voltages before and after mitigation for the 11 controller system.

IX. CONCLUSION AND FUTURE WORK

The proposed algorithm provides a considerable corrective action to the operating points of non-failed controllers to maintain the bus voltages within practically acceptable levels. In situations of failure of non-critical controllers, the algorithm provides corrective results that can offset the effect of failure.

The matrix inversion that is performed in the algorithm is possible for all practical configurations except the case all buses are connected to all other buses. Since such a situation is highly impractical, the algorithm can be said to be unrestricted by system topology. Given that the matrices are sparse, suitable matrix inversion techniques can be applied to make the computations feasible for larger systems.

The proposed methodology offers insights into designing operating ranges of controllers to obtain better compensation in situations of failure, computing the support a controller is expected to provide, and replacing it with the maximum value possible if the ceiling is exceeded. However, for cases where there exists no coupling effect of adjacent lines on a transmission line, this algorithm cannot be implemented.

While the presented work considers a single operating point at failure, future work would include accounting for dynamically changing operating points, transients and inclusion of trajectory predictive algorithms for predicting the new operating points based on transients. The algorithm can be suitably modified extended to malfunctioning controllers and adversarial controller operation due to cyber-attacks.

ACKNOWLEDGMENT

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