Research Article

Power flow management analysis using compensating techniques for managing congestion within electrical energy network

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Abstract

In a deregulated electrical energy system with increasing penetration of renewable energy sources, rescheduling of the power generation(s) is required, and it is going to congest some of the power lines in the complex power system. The power flow can be managed using different compensating techniques. This study presents power flow management analysis using selected compensation technologies (i.e. series, shunt, series-shunt, and D-FACTS) for congestion alleviation. In this work, an IEEE 6 bus distributed network is used and the mentioned compensating techniques are evaluated for congestion management considering a case of power line outage. It is observed some of the power lines are overloaded by 10%. To reduce the overloading; the series, shunt, series-shunt, D-FACTS compensation technologies are used and found that they can reduce the active power overloading of the congested line by 27%, 9.5%, 12%, and 27% respectively. But the apparent power congestions can be reduced using series and D-FACTS techniques by 14% compare to shunt and series-shunt techniques. It is affirmed that the D-FACTS can effectively manage the power flow compare to other compensation techniques and can offer other benefits (e.g. voltage quality, line power flows, injection of power at the buses, reduction in power losses, etc.).

Keywords Power flow management · Power flow compensation techniques · Distributed-FACTS (d-FACTS) · Electrical power flow congestion · Interconnected electrical energy network

1 Introduction

The electrical energy system is facing challenges due to the increasing penetration of renewable energy sources as well as restructuring of the electrical energy balance market [1]. They are affecting organizational and techno-economic operation of electrical energy system [2]. A regulated electric energy system is transforming into the liberalized electrical energy market to facilitate the integration of renewable energy sources as well as competitive participation of different power generation plants [3]. Due to restructuring, power generation companies are effectively trying to get more operational benefits in the electrical energy market [4]. In a deregulated power system, rescheduling of the power generation may congest some of the power lines due to complex electrical energy network [5]. The congestion may increase the loading of some of the power line(s), and it is going to affect the overall power system operation (e.g. voltage stability, tripping of power lines, thermal limits, system stability and security, etc.). The congestion in some of the power line(s) may results into blackout. Due to overloading, some of the power lines may reach to its thermal limits as well as voltage limitations at the network buses [6].

The congestion within the power system network is going to affect power system dynamics and control. The

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congestion in the electrical energy system can be managed through rescheduling of some of the generations as well as implementing appropriate devices within the power system network. The congestion in the affected power lines can be managed using appropriate technologies (e.g. transformer operation with phase shifting/tap changing, reactive power compensation, implementation and operation of compensating devices, etc.) [7].

The congested power lines loading can be reduced using compensation technologies (e.g. series, shunt, series-shunt, D-FACTS, etc.) by reducing the power flow. The compensation technologies can help in reducing the congestions in overloaded power line(s), it can contribute in reducing the thermal loading and hence increasing the lifetime of power line(s). The transient performance of the power lines can also be improved with appropriate control of compensation systems during sudden load disturbances [8]. The compensation technique has the capability in controlling the power angles between the two buses for managing the power injection from the intermittent renewable energy sources [9].

In this work, the selected compensating techniques viz. series, shunt, series-shunt, D-FACTS are analyzed for a typical IEEE 6 bus system for finding suitable application(s) of them within the electrical energy network for reducing the congestion in the power line(s) due to abnormal operation (e.g. outage of a line). The performance evaluations of considered compensating methods for power flow controls are studied to distinguish their potential applications for congestion alleviation in the electrical energy network.

2 Compensation technologies for managing power line(s) capacity

The compensation technologies can effectively contribute in managing the capability of the power line(s) and can effectively contribute in managing the congestions in some of the power lines, which is going to occur in the reregulated electrical energy system [10]. The major contributions of compensation techniques in the power system operation are:

- Transient performance improvement in power line(s) during load disturbances by controlling the load angles between the two buses/nodes.
- Damp out the oscillations in improving the system dynamics through controllers of the compensation devices.
- To contribute in managing the reactive power through power lines in reducing the loading as well as voltage regulations between the nodes.
- Managing the effective impedances of lines for power flow control as well as impact on phase shifting operation of transformers.
- To contribute in reducing geomagnetic effects for mitigating lower frequency effects.

In this work, the compensation technologies (i.e. series, shunt, series-shunt, D-FACTS) are considered for power flow management in the congested power line(s) during abnormal operation of a typical power network (i.e. IEEE 6 bus system). The performance of the selected power network is analyzed for evaluating the effectiveness of the mentioned compensation techniques for enhancing the load capability limits of power line(s) during a typical abnormal condition [11].

2.1 Power flow analysis in normal operation

During normal operation, power flow analysis of a typical IEEE 6 bus system without any compensation techniques is analyzed [12]. The power ratings of the considered generators and loads are systematically presented in Fig. 1. The power flows in different power lines as well as power line losses and reactive power at each nodes are marked in the Fig. 1 [13]. It is observed that power line between buses 1 and 5 is relatively more loaded (i.e. 93.5%) than the other power lines, and the least loaded (i.e. 23.5%) power line is between buses 5 and 6.

As shown in Fig. 1 in the normal operating conditions, the load flow data is obtained and tabulated in the Table 1 The power flows of all the transmission lines are within their thermal limits.

2.2 Power flow analysis during a typical outage of a line

Due to abnormal operating condition, there may be chances some of the power lines may get overloaded and may get disconnected within the network. In this study, it is considered a power line (i.e. line between 2 and 5) is having an outage due to some abnormal situation. Under this circumstance to fulfil the load requirement, the power flows through the remaining power lines are changed effectively and reported in Fig. 2. It is observed that power line between 1 and 5 is getting overloaded by 104% and the power line between 3 and 6 is loaded at 83%. The power flow through line 1–5 is higher than the rated capacity, and it is going to affect the thermal limits. It is required to introduce some. It is noticed that the power flow in line 1–5 is increased beyond its thermal limit.

In this work, this violation is considered as a reference condition for further work in applying all the proposed

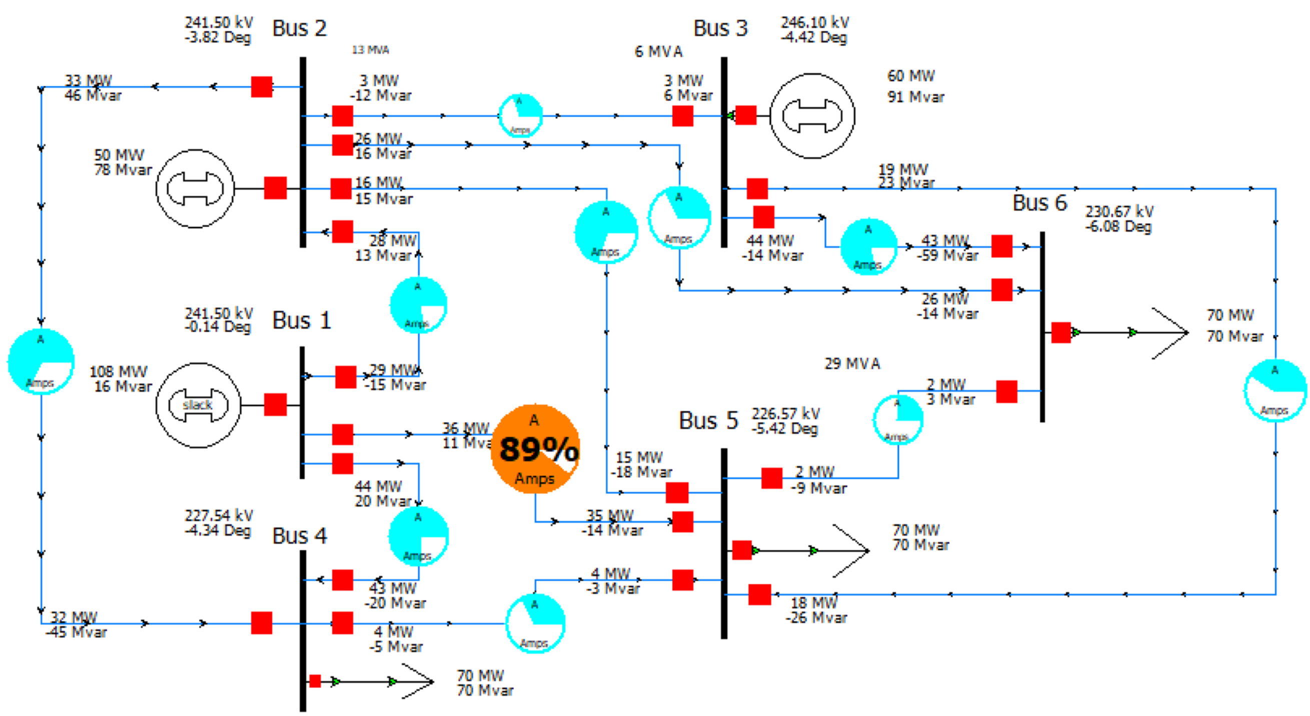

Fig. 1 Power flows in an IEEE 6 bus system during a typical normal operation

Table 1 Power flow data of IEEE 6 bus system under normal condition

Bus	Line no.	MW flow	MVAr flow	MVA flow	MVA limit	MW loss	MVAR loss
1–2	1	28.7	15.4	32.6	40	0.91	−2.59
1–4	2	43.6	20.1	48	60	1.09	0.19
1–5	3	35.6	11.4	37.4	40	1.08	−2.18
2–3	4	2.9	−12.3	12.6	40	0.04	−6.54
2–4	5	33.1	46.1	56.7	80	1.51	0.93
2–5	6	15.5	15.5	21.9	30	0.5	−2.64
2–6	7	26.3	15.9	30.8	90	0.6	1.72
3–5	8	19.1	23.3	30.2	70	1.1	−2.9
3–6	9	43.7	62.3	76.1	90	1.04	3.04
4–5	10	4.1	−4.9	6.4	20	0.04	−7.72
5–6	11	1.7	−9.3	9.4	40	0.04	−5.79

compensation techniques (i.e. series, shunt, series-shunt, D-FACTS) to analyze their effectiveness for enhancement of line loading abilities and other parameters for the relative analysis and their applications. The power flow analysis during outage of a line is presented in the Table 2.

3 Application of compensation techniques for congestion reduction during outage of a power line

The compensation technologies can effectively contribute in managing the capability of the power lines and they can effectively contribute in managing the congestions in some of the overloaded power lines, which is going to occur in the deregulated environment of electrical energy system. The compensation technologies (e.g. series, shunt, series-shunt, D-FACTS, etc.) are used to analyze the power

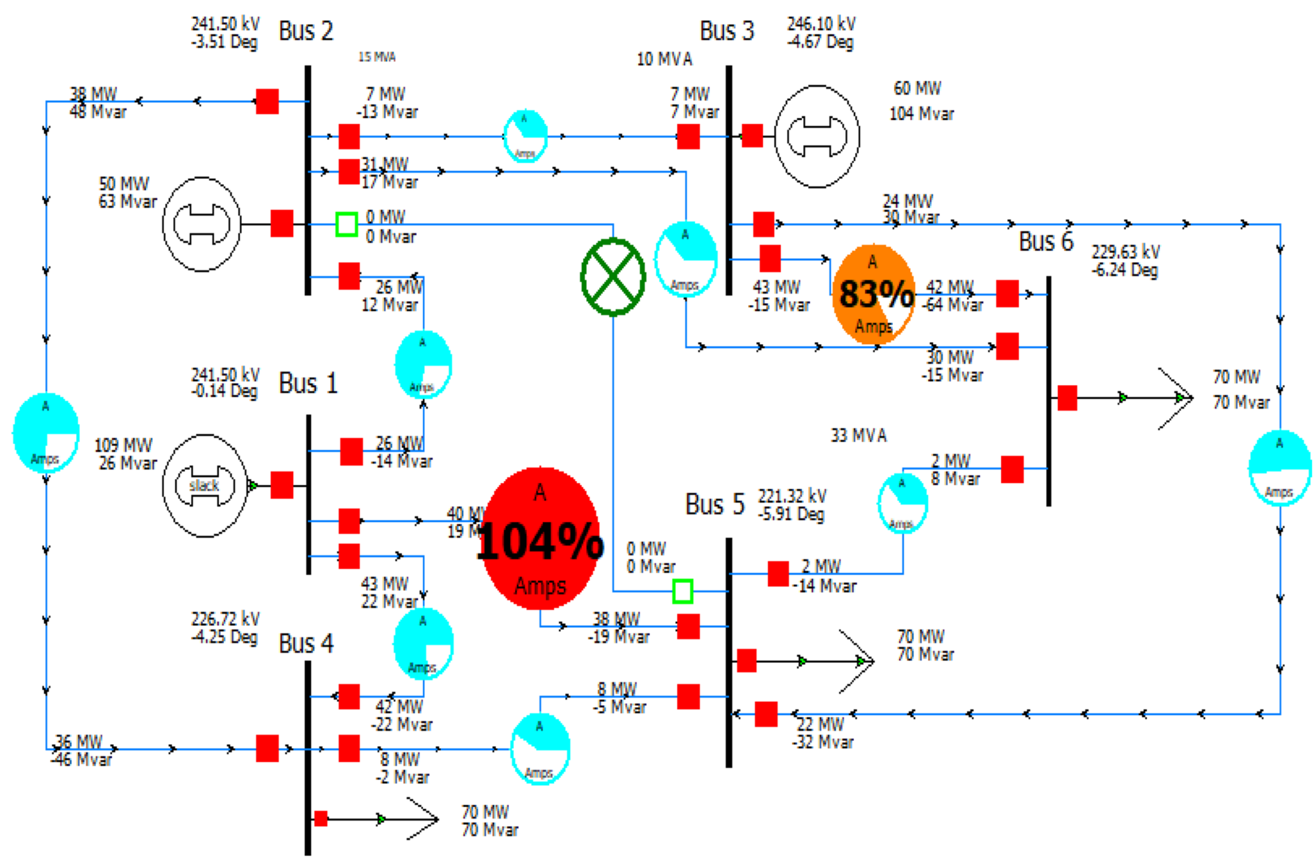

Fig. 2 Power flows in an IEEE 6 bus system during outage of line 2–5

Table 2 Power flow results during outage of the line 2–5

Bus	Line no	MW flow	MVAr flow	MVA flow	MVA limit	MW loss	MVAr loss
1–2	1	26.3	−14.4	30	40	0.76	−2.88
1–4	2	43.1	22.1	48.4	60	1.11	0.29
1–5	3	39.7	18.5	**43.8**	40	1.49	−0.5
2–3	4	7.1	−13	14.9	40	0.07	−6.41
2–4	5	37.6	47.6	60.7	80	1.72	1.36
2–5	6	0	0	0	30	0	0
2–6	7	30.9	16.9	35.2	90	0.79	2.25
3–5	8	24	30.5	38.8	70	1.77	−1.34
3–6	9	43	67.3	79.9	90	1.14	3.57
4–5	10	7.9	−1.9	8.1	20	0.14	−7.32
5–6	11	−1.8	−13.8	13.9	40	0.13	−5.37

Highlighting good results obtained

flows in the selected IEEE 6 bus system during outage of a typical line (i.e. line 2–5).

3.1 Series compensation

In this study, power line 1–5 is overloaded, and to reduce its congestion, series compensations are introduced in the power network [14]. The lines 1–4 and 1–2 are used for series compensation. After inclusion of series compensation, the lines' reactance (capacitor in service mode) is changed and the power flows through these lines are increased. Under this situation, the power flow results with application of series compensation in lines 1–4 and 1–2 are systematically represented in Fig. 3.

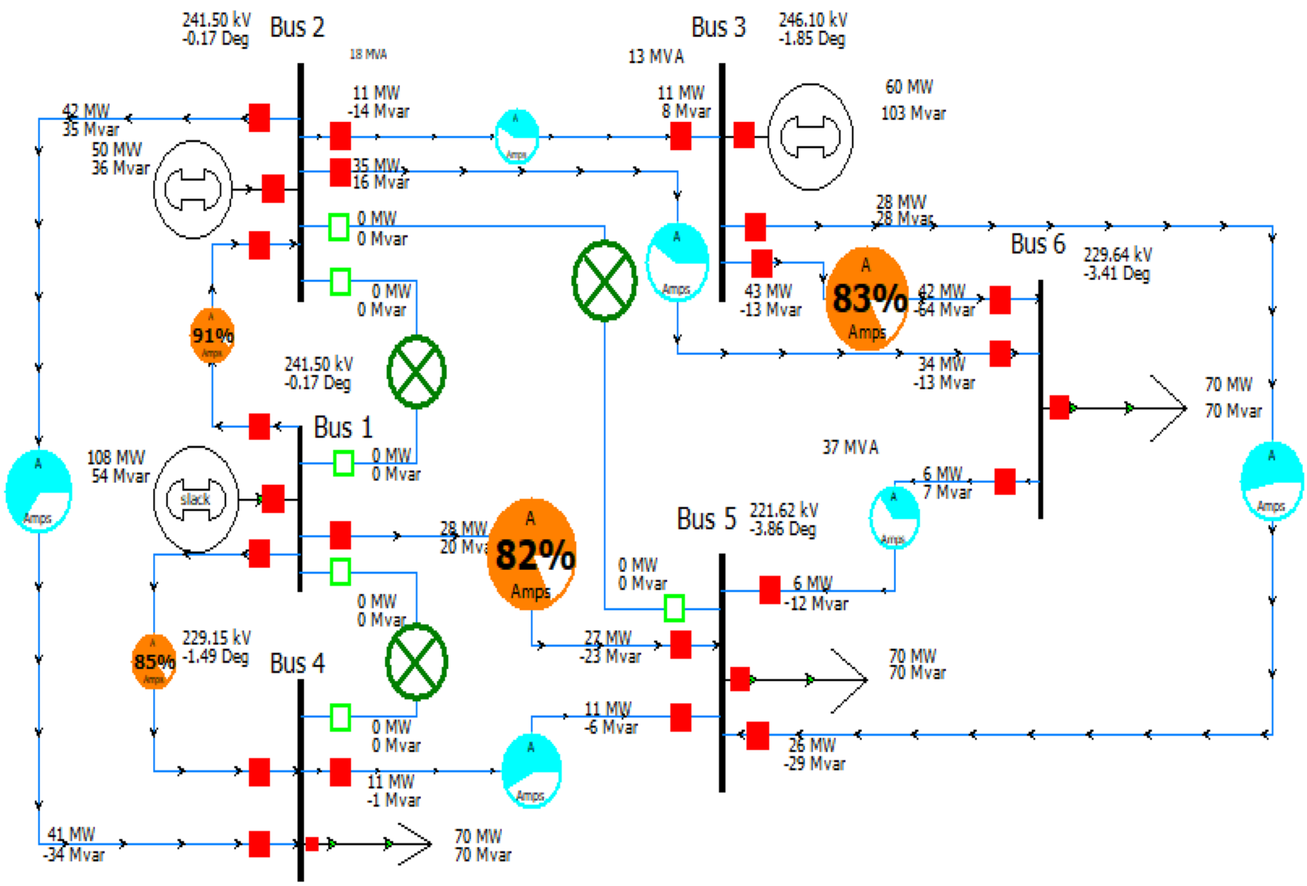

Fig. 3 Power flows in an IEEE 6 bus system during outage of line 2–5 under series compensations in selected power lines (1–2, 1–4)

Table 3 Results with series compensation during the outage of line 2–5

Bus	Line no	MW flow	MVAr flow	MVA flow	MVA limit	MW loss	MVAr loss
1–2	1	38.2	− 0.4	**38.2**	40	0	0
1–4	2	42	33.4	**53.7**	60	1.38	− 1.44
1–5	3	28	20.2	**34.5**	40	0.97	− 2.46
2–3	4	11.1	− 13.7	17.7	40	0.11	− 6.22
2–4	5	42	34.5	54.4	80	1.38	0.66
2–5	6	0	0	0	30	0	0
2–6	7	35.1	15.6	38.4	90	0.94	2.68
3–5	8	28.2	28.2	39.9	70	1.84	− 1.19
3–6	9	42.7	67.3	79.7	90	1.14	3.54
4–5	10	11.3	− 1.2	11.3	20	0.27	− 7.14
5–6	11	− 5.6	− 12.1	13.3	40	0.13	− 5.39

Highlighting good results obtained

It is observed that the loading of earlier overloaded line 1–5 is reduced to 82% from 104% (without compensation, Fig. 2); and in the series compensation power lines 1–5 and 1–4, the loading is changed to 91% and 85% respectively. But, the loading of power line 3–6 is remaining the same (i.e. 83%).

The power flow result shows that the overloading of line 1–5 is diverted through the power lines 1–4 and 1–2 within their limits, during the violation of the power line 2–5 (i.e. outage) as tabulated in Table 3.

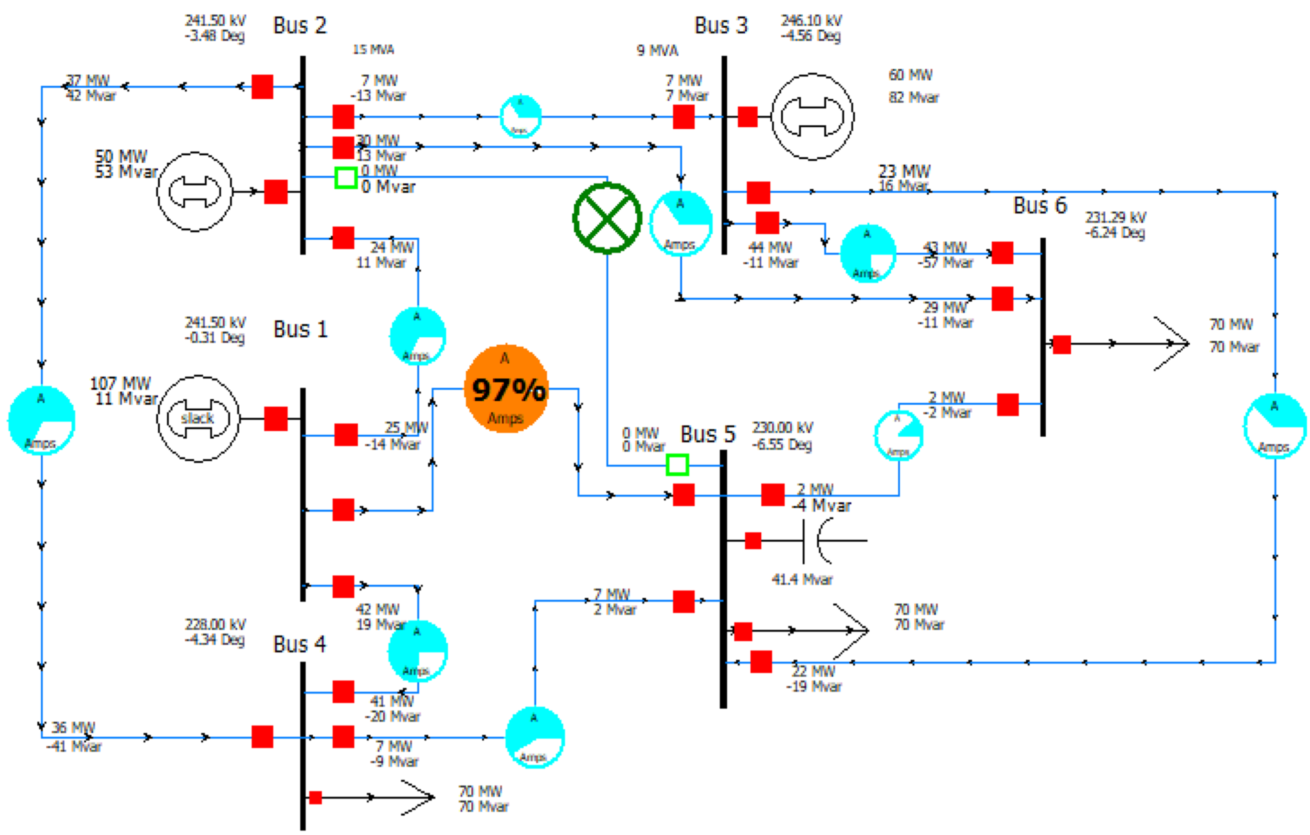

Fig. 4 Power flows in an IEEE 6 bus system during outage of line 2–5 under shunt compensation at bus 5

3.2 Shunt compensation

The shunt compensators can also be used to reduce the overloading of the line during abnormal power system operation (e.g. outage) [15]. In this study, to analyze the power flow during outage of line 2–5, shunt compensation is introduced at bus no. 5. It is represented in the Fig. 4.

The power flows through power lines are systematically represented in the Fig. 4 during outage of line 2–5 with introduction of shunt compensation at bus 5. It is observed that line 1–5 loading is reduced to 97% compare to 104% (Fig. 2), and the power flows through remaining power lines are significantly below the capacities of the respective power lines.

The shunt capacitor of the rating of 41.4Mvar is used at bus 5, which contributes in reducing the power flow of line

Table 4 Load flow results of shunt compensation during outage of L2–5

Bus	Line no	MW flow	MVAr flow	MVA flow	MVA limit	MW loss	MVAr loss
1–2	1	24.3	− 13.5	27.8	40	0.65	− 3.11
1–4	2	41.7	18.4	45.6	60	0.98	− 0.25
1–5	3	40.9	0.70	39.8	40	1.22	− 1.81
2–3	4	6.5	− 12.9	14.5	40	0.06	− 6.44
2–4	5	37.2	39.9	54.6	80	1.39	0.69
2–5	6	0	0	0	30	0	0
2–6	7	30.0	12.0	32.3	90	0.66	1.89
3–5	8	22.5	10.2	24.6	70	0.71	− 3.9
3–6	9	43.9	56.6	71.6	90	0.92	2.43
4–5	10	6.5	− 12.1	13.8	20	0.22	− 7.62
5–6	11	− 2.3	− 0.4	2.3	40	0.01	− 6.1

Highlighting good results obtained

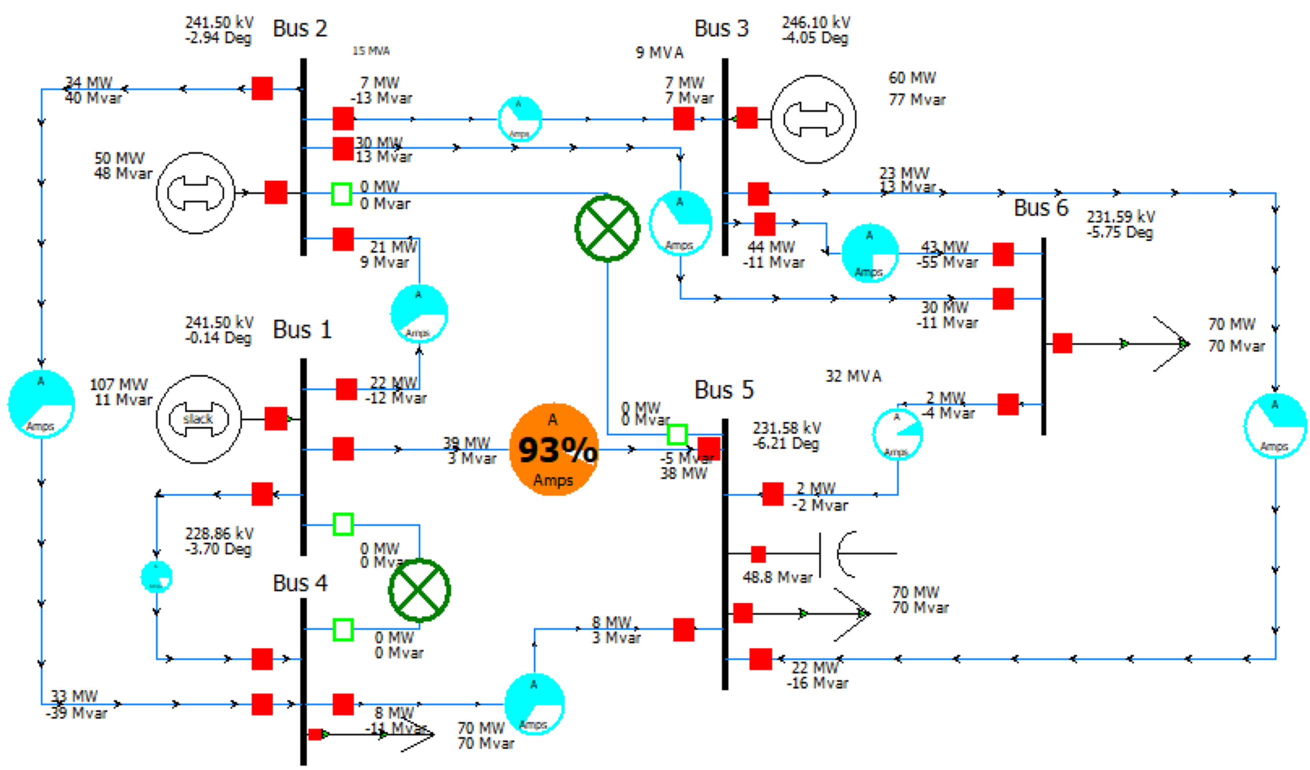

Fig. 5 Power flows in an IEEE 6 bus system during outage of line 2–5 under series-shunt compensation

1–5 by diverting it through the nearby lines connected on bus 5. The power flow results are presented in the Table 4.

3.3 Series-shunt compensation

The series-shunt compensation devices can also be used effectively in reducing the overloading of the power lines during the outage conditions. In this compensation technique, the series compensation contributes in changing the reactance of the power line(s), and shunt compensation modifies the load impedance [16]. In this study, a power line 2–5 is considered as outage line, and observed that the line 1–5 is congested (Fig. 2). The series compensation is introduced in the power line 1–4 and the shunt compensation at bus 5. It systematically represented in the Fig. 5.

With introduction of series-shunt compensation, the power flow calculations are performed for considered IEEE 6 bus system, during the outage of power line 2–5 and they are analytically marked in the Fig. 5. It is observed that the overloading of line 1–5 is reduced to 93% compare to 104% (without compensation—Fig. 2).

Table 5 Power flow results with series-shunt compensation during the outage of line 2–5

Bus	Line no.	MW flow	MVAr flow	MVA flow	MVA limit	MW loss	MVAr loss
1–2	1	21.8	− 12.4	25.1	40	0.53	− 3.36
1–4	2	46	20	50.2	60	1.19	− 0.27
1–5	3	39.1	3.4	39.2	40	1.14	− 2.08
2–3	4	6.8	− 13	14.6	40	0.06	− 6.43
2–4	5	34.2	39.6	52.3	80	1.28	0.47
2–5	6	0	0	0	30	0	0
2–6	7	30.3	12.6	32.9	90	0.69	1.96
3–5	8	22.9	12.9	26.3	70	0.81	− 3.65
3–6	9	43.8	58.1	72.7	90	0.95	2.58
4–5	10	7.7	− 10.5	13	20	0.21	− 7.6
5–6	11	− 2.5	− 2.2	3.3	40	0.01	− 6.06

Highlighting good results obtained

The power flows in the remaining power lines are significantly lower than their respective power lines' capacities. Power flow results with series shunt compensation can be observed in Table 5 given below.

3.4 Distributed FACTS (D-FACTS)

The FACTS technologies can be used as a tool in managing the power system network during congestions as well as to manage the power flows with intermittent renewable energy generations and demand side management. The FACTS technologies with controllers and power conditioning devices can effectively contribute in managing the power flows in the selected power lines compare to other compensation devices installed at the sub-stations. The power conditioning devices based distributed FACTS (i.e. D-FACTS) can be introduced in the power lines [17–20]. In this study D-FACTS is introduced and it is represented in Fig. 6.

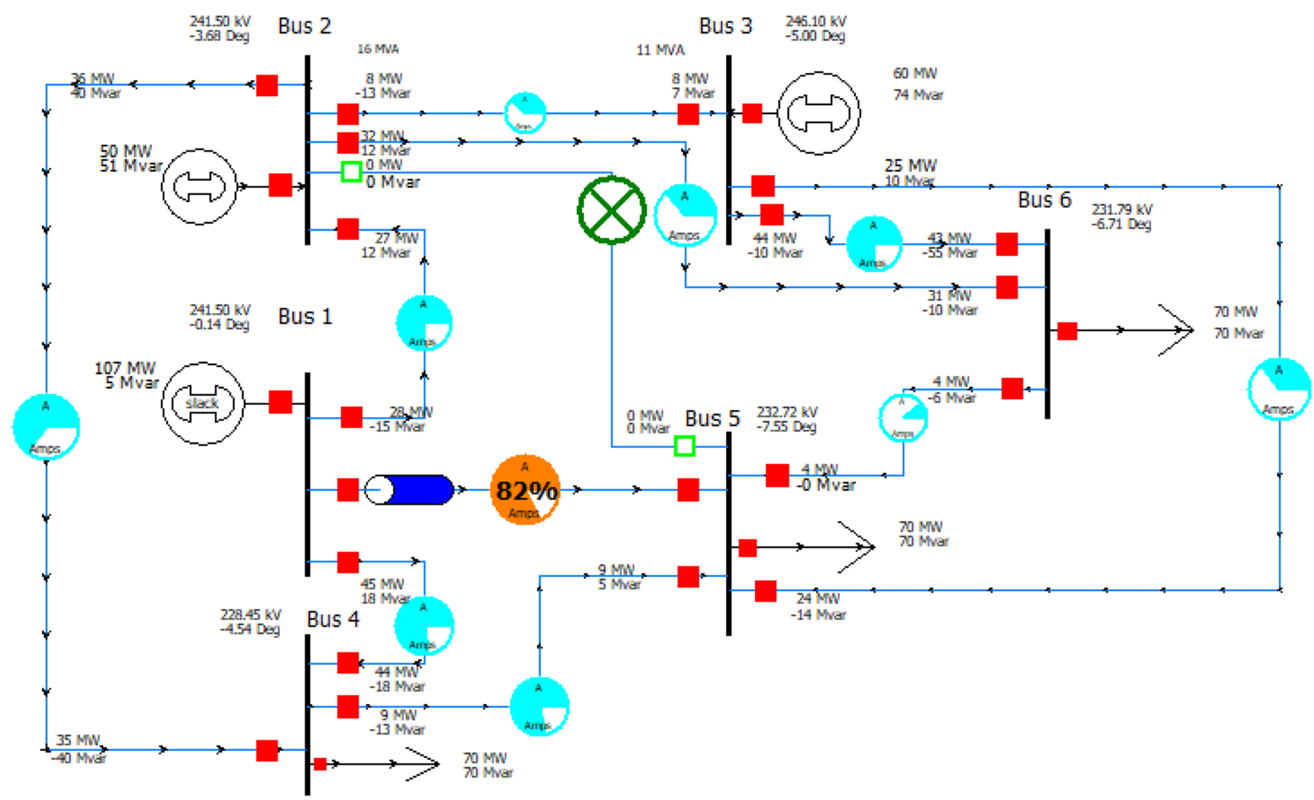

Fig. 6 Power flows in an IEEE 6 bus system during outage of line 2–5 under D-FACTS

Table 6 Power flow results with D-FACTS during the outage of line 2–5

Bus	Line no	MW flow	MVAr flow	MVA flow	MVA limit	MW loss	MVAr loss
1–2	1	27.6	− 15	31.4	40	0.84	− 2.73
1–4	2	45	17.9	48.4	60	1.1	0.22
1–5	3	34.5	1.9	34.5	40	0.88	− 1.86
2–3	4	8.4	− 13.3	15.7	40	0.08	− 6.36
2–4	5	36.4	40.4	54.3	80	1.38	0.67
2–5	6	0	0	0	30	0	0
2–6	7	32	11.7	34.1	90	0.74	2.11
3–5	8	24.5	10.2	26.6	70	0.81	− 3.67
3–6	9	43.7	57.2	72	90	0.93	2.48
4–5	10	8.9	− 12.6	15.4	20	0.31	− 7.42
5–6	11	− 4.1	− 0.3	4.1	40	0.02	− 6.05

Highlighting good results obtained

In this work, D-FACTS is applied (in a power line 1–5) to analyze the power flow in the considered IEEE 6 bus system during the outage of power line 2–5. With introduction of D-FACTS, the earlier congested power line 1–5 loading is reduced to 82% compare to 104% (without compensation—Fig. 2). The power flows in the network are analytically represented in Fig. 6. The power flows in the remaining power lines are relatively lower compare to inclusion of other compensation techniques as described in the Sects. 3.1, 3.2, 3.3. From the results in Table 6 and through analysis of the results, it is observed that with introduction of D-FACTS, the voltage quality is improved and the power line losses are minimized compare to other considered compensating techniques [21–24].

4 Economic comparison

It is a general concord that the future transmission network will need to be smart, Fault-tolerant, dynamically controllable and energy and asset efficient. Technically proven approach for the active power flow control of the grid and to make grid smart and controllable is through the use of Flexible AC Transmission System or FACTS. Flexible AC transmission system (FACTS) is proven for managing the power flow for effective utilization of the power lines during contingency conditions, reducing line loading, etc. The FACTS devices can also contribute to demand-side management, and also managing the load congestions within the power system network.

In the electricity market, demand-side management is going to be a key factor for efficient load management within the power system using the FACTS devices appropriately. The new power lines may contribute to reducing the power capabilities of the existing power lines, but the capital cost of power lines may be in the range of US $ 0.5–3.5 million/mile. The FACTS components are relatively expensive and due to that, their uses in the power lines have restricted. FACTS devices broadly classified in Series, shunt, series-shunt compensators. Though this technology is proven since long, it has not yet seen widespread commercial acceptance due to many reasons like (i) Requirement of high power rating for the use of high power GTO or GCT devices with significant engineering efforts increases cost. (ii) High Insulation requirement due to very high fault current (up to 6000 Amp) increases stress on power electronics system (especially series system which is needed for power flow control) further increases cost. (iii) To achieve a high-reliability level and for the maintenance and operation of the system, a highly skilled workforce is required which further increases cost and very high total cost of ownership [21, 25].

The latest concept of distributed approach for realizing FACTS devices (especially series FACTS devices) which proposes a similar approach to the implementation of high power FACTs devices is discussed as a techno-economical alternative in this work. This Distributed FACTS provides higher performance at a lower cost for enhancing T&D system reliability, controllability, improving asset utilization, and end-user power quality while minimizing cost and environmental impact [25]. Presented work includes Comparison of Series, shunt, series-shunt compensators with the distributed FACTS for power flow control, and thus congestion management. For the same, detailed technical comparison has been prepared using IEEE 6 bus test system and presented in chapter 4 of the work report. This FACTS device typically costs U.S. $120–U.S. $150 per KVA whereas D-FACTS Cost expected to be well below the U.S. $100 per KVA. In addition to the cost, other numerous advantages of Distributed FACTS are even more compelling [25].

5 Results and discussion

In this study, the compensation techniques (i.e. series, shunt, series-shunt, D-FACTS) are analyzed for their effectiveness for enhancement of line loading abilities and

Table 7 Relative comparison of the compensation techniques

Parameters of comparison	Normal case	Contingency outage 2–5	Compensation techniques (during outage of line 2–5)			
			Series	Shunt	Series-shunt	DFACTS
MVA flow of line 1–5 (40 MVA limit)	37.4	43.8	**34.5**	39.8	39.2	**34.5**
Total MW generation	217.94	219.11	218.15	216.83	216.85	217.09
Total MVAr generation	185.51	193.64	193.01	128.23	136.8	130.08
Total MW losses	7.95	9.12	8.16	6.82	6.87	7.09
Total MVAr losses	− 24.48	− 16.35	− 16.96	− 24.22	− 24.44	− 22.6
Lowest bus voltage (kV) due to outage of line 2–5	NA	221.318	221.6	233.2	231.5	232.7

Highlighting good results obtained

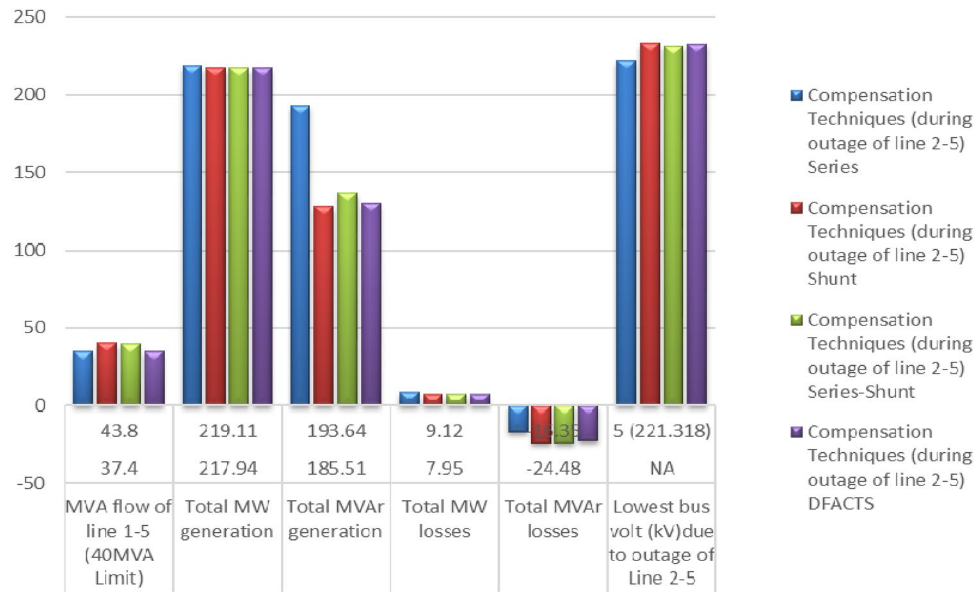

Fig. 7 Comparison of the Compensation techniques

other parameters [26]. The power flows congestion management results for each compensating techniques are presented in the Sect. 3, for outage of a power line in a typical IEEE 6 bus network. In case of power outage in a line (i.e. power line 2–5 in IEEE 6 bus system), some of the power line(s) are getting overloaded. To reduce overloading; the series, shunt, series-shunt, D-FACTS compensation technologies are analyzed and compared. The active power overloading of the congested line is reduced by 27%, 9.5%, 12%, and 27% respectively. But the apparent power congestions can be reduced using series and D-FACTS techniques by 14% compare to shunt and series-shunt techniques. The apparent power congestions can be reduced using series and D-FACTS techniques by 14% compare to shunt and series-shunt techniques. The relative comparisons of the implemented compensation techniques, with the same outage of a power line in the IEEE 6 bus system, is presented in the Table 7.

The D-FACTS can effectively manage the power flow compare to other compensation techniques. The D-FACTS can offer many benefits for power network management (e.g. voltage quality, line power flows, injection of power at the buses, reduction in power losses, etc.) relative comparison of analyzed compensation techniques are presented in Fig. 6.

6 Conclusion

In deregulated electrical energy system and with increasing penetration of renewable energy sources, the interconnected power system has advantages. In interconnected electrical network, power sharing is becoming challenging; and it can only be handled with the proper control on transmission network. In this study, selected compensating techniques are compared for the power flow management of the network and they are to enhance line performance and to mitigate the chances of power lines congestion. The compensation technologies (i.e. series, shunt, series-shunt, D-FACTS) are evaluated for their performances in a typical IEEE 6 bus system to distinguish their potential applications for congestion alleviation in the power system. It is concluded that the mentioned compensation technologies can effectively contribute in managing the capability of the power lines, which is going to occur in the deregulated environment of electrical energy system, as well as with increasing penetration of intermittent renewable energy sources. This study finds that the series and D-FACTS are reducing the apparent power congestions in the affected power line compare to shunt and series-shunt. It is witnessed that the D-FACTS can effectively manage the power flows very well compare to other compensation techniques with additional advantages of power quality. The D-FACTS devices can be included in the power lines for efficiently changing the effective power line impedance, and hence contributing in the network stability and control, as well as managing the loading congestions within the power lines and reducing the thermal losses and managing voltage regulations (Fig. 7).

Compare to other compensation techniques, D-FACTS can be used to overcome the problems of power losses minimization and voltage regulations. It is necessary to do further analysis and investigations for deciding, which power lines can be used as appropriate choice for D-FACTS locations. The D-FACTS can be used for improving the power system stability and control through development of effective cyber secure control techniques for operation of D-FACTS.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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