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Emergency congestion management of power systems by static synchronous series compensator

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ABSTRACT

From a transmission system point of view, any overload on the grid lines during operation in situations such as peak load or emergency conditions include line outage or generator outage, is refers to congestion. Generally, the congestion can be managed by controlling power flow. On the other hand, series compensation has a significant role in control power flow; therefore, series compensation equipment like fixed series capacitor (FSC), thyristor-controlled series capacitor (TCSC), and static synchronous series compensator (SSSC) can be used for congestion management. In this paper, an SSSC is used in a transmission line to manage congestion in emergency conditions, line outage and generator outage. The congestion rent contribution method has been used to determine the location of the SSSC in the IEEE 14-bus test system. This technique finds the transmission line 1-2 (from bus 1 to bus 2) is the best location of the SSSC to reduce congestion. After installing an SSSC in the specified line, simulation results show that the power flow has been controlled, leading to reducing the congestion. In other words, the effectiveness of the SSSC can be seen in reducing the total congestion rent, the total generation cost, and network losses.

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1. INTRODUCTION

One of the most critical issues related to restructured power systems is congestion in transmission networks. Some transmission lines can be overloaded for various reasons, such as line outage, generator outage, and power exchange contract changes. Another major factor in the occurrence of congestion is the transmission, formation, and creation of contracts between market components. Because in a competitive market, consumers are always willing to buy the necessary power from cheaper production units, concentrating high-efficiency and cheaper units in a specific area of the network lead to increased power flow in the lines and transmission equipment of the related area; as a result, the transmission congestion intensifies. The significant effects of congestion are: i) preventing the creation of new contracts, ii) inability to perform existing contracts, iii) monopoly price in some areas, iv) damage to electrical equipment in the system, and v) increasing the price of electricity in some areas. Various methods have been proposed by researchers and those involved in the electricity industry to reduce and manage congestion, such as developing new transmission lines, operation of conventional compensation devices, flexible ac transmission systems (FACTS) devices, nodal pricing, zonal pricing, and redispatching [1]–[3].

FACTS devices can enhance the control of the system by power electronic components. The major applications of FACTS devices include power flow control, increasing transmission line capacity, voltage control, reactive power compensation, improve stability, enhance power quality, and flicker reduction [4] that numerous researches have been arranged on surveys of them [5]–[13].

The limitation of power transmission can be eliminated or reduced by controlling the power flow. Hence, the use of series-connected FACTS devices like thyristor-controlled series capacitor (TCSC) and static synchronous series compensator (SSSC) for congestion management is beneficial. SSSC and TCSC are a type of variable series compensation. However, SSSC has more advantages than a TCSC, such as higher speed, more comprehensive control range, and no use of bulky capacitors and reactors [14], [15]. As a result, this article investigates the role of the SSSC on congestion management of transmission systems. The application of the FACTS devices on control power flow and congestion management has been studied in various papers [15]–[20]. Notably, the focus of the articles [21]–[24] is on congestion management using the SSSC. This paper presents the role of SSSC on congestion management in an emergency condition. The rest of this paper is organized as shown in; The SSSC is introduced in section 2. Section 3 describes the congestion rent contribution method. Line outage and generator outage as emergency conditions are reviewed in section 4. The Simulation results are given in section 5. Finally, the paper ends with a conclusion in section 6.

2. STATIC SYNCHRONOUS SERIES COMPENSATOR

An SSSC is included of voltage source converter (VSC), diodes, direct current (DC) link capacitor and connected in series with the transmission line by a coupling transformer as shown in Figure 1. This device can provide the series compensation by injecting the controllable voltage into the line and thus changing the transmission line impedance. The SSSC can exchange active and reactive power with the power system, and as a result, active and reactive power flow is controllable [14], [25].

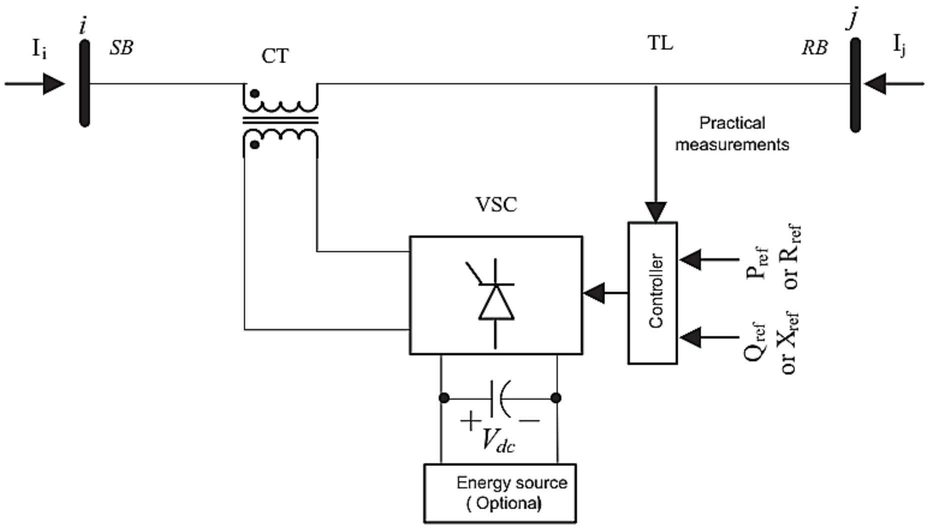

Figure 1. Diagram of the SSSC connected to a transmission line [25]

An equivalent circuit of the SSSC is shown in Figure 2. In the equivalent circuit, the SSSC is depicted by a voltage source ($\overline{V_s}$) in series with a transformer impedance *(Z_s)*. The power flow of line *i*–*j* can be controlled by adjusting $\overline{V_s}$ [25].

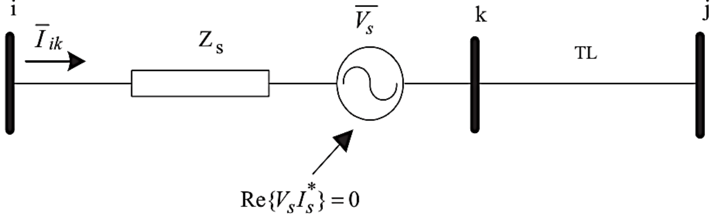

Figure 2. Equivalent circuit of the SSSC (bus *k* is an auxiliary bus) [25]

Based on the SSSC equivalent circuit and considering the complex voltage of buses, $\bar{V}_i = V_i\angle\varphi_i$, $\bar{V}_k = V_k\angle\varphi_k$ and $\bar{V}_s = V_s\angle\delta_s$, the power flow equations between buses *i* and *k* can be obtained in (1)-(4) [25]:

$$P_{ik} = V_i^2 G_s - V_i V_k[G_s\cos(\varphi_i - \varphi_k) + B_s\sin(\varphi_i - \varphi_k)] \\ -V_i V_s[G_s\cos(\varphi_i - \delta_s) + B_s\sin(\varphi_i - \delta_s)] \quad (1)$$

$$P_{ki} = V_k^2 G_s - V_k V_i[G_s\cos(\varphi_k - \varphi_i) + B_s\sin(\varphi_k - \varphi_i)] \\ +V_k V_s[G_s\cos(\varphi_k - \delta_s) + B_s\sin(\varphi_k - \delta_s)] \quad (2)$$

$$Q_{ik} = -V_i^2 B_s - V_i V_k[G_s\sin(\varphi_i - \varphi_k) - B_s\cos(\varphi_i - \varphi_k)] \\ -V_i V_s[G_s\sin(\varphi_i - \delta_s) - B_s\cos(\varphi_i - \delta_s)] \quad (3)$$

$$Q_{ki} = -V_k^2 B_s - V_k V_i[G_s\sin(\varphi_k - \varphi_i) - B_s\cos(\varphi_k - \varphi_i)] \\ +V_k V_s[G_s\sin(\varphi_k - \delta_s) - B_s\cos(\varphi_k - \delta_s)] \quad (4)$$

where G_s and B_s are the conductance and susceptance of a transformer impedance, respectively. The active power exchanged through the DC link can be determined as (5)-(6) [25]:

$$PE = Re\{\bar{V}_s\, \bar{I}_{ik}^*\} = 0 \quad (5)$$

$$Re\{\bar{V}_s\, \bar{I}_{ik}^*\} = V_i V_s[G_s\sin(\varphi_i - \delta_s) - B_s\cos(\varphi_i - \delta_s)] \\ +V_k V_s[G_s\sin(\varphi_k - \delta_s) - B_s\cos(\varphi_k - \delta_s)] \quad (6)$$

where $\bar{I}_{ik}$ is the complex current of the line.

3. CONGESTION RENT CONTRIBUTION METHOD

Initially, the congestion rent contribution method has been proposed in [26]. This method is based on locational marginal price (LMP) differences and congestion rent, respectively. The congestion rent contribution method has been used in several papers for locating series FACTS devices (or series part of shunt-series FACTS devices) [15], [26]–[28].

3.1. Definition of LMP

Locational marginal pricing (also termed the spot price) is a market-pricing strategy employed to manage the efficient use of the transmission system when congestion happens on the power system. When a system becomes congested, the impacts appear in the prices and LMP increases. These LMPs are time-varying and directly relate to the actual operating cost of the system [26], [29], [30]. LMPs are obtained by optimal power flow (OPF), and congestion rent is a function of LMP difference and power flow [26].

3.2. Formulation of method

The congestion rent of line *i*–*j* (CC_{ij}) is obtained as [15]:

$$CC_{ij} = |LMP_i - LMP_j| * |P_{ij}|\ (\$/hr) \quad (7)$$

where LMP_i and LMP_j are the locational marginal price at buses *i* and *j*, respectively, and P_{ij} is the power flow between buses *i* and *j*. The total congestion rent (*TCC*) is expressed as (8):

$$TCC = \sum_{ij=1}^{N_L} CC_{ij}\ \ (\$/hr) \quad (8)$$

where N_L is the total number of lines. The congestion rent contribution of line *i*–*j* (CCC_{ij}) is (9).

$$CCC_{ij} = \frac{CC_{ij}}{TCC} \quad (9)$$

3.3. Procedure of method

The procedure of the congestion rent contribution method is defined in the following steps [15], [26]: i) Run the OPF in the base case to get the LMP at all buses and the power flow (P_{ij}) in all lines;

ii) Calculate the congestion rent (CC_{ij}) based on (7) for all lines; iii) Calculate the total congestion rent (TCC) based on (8); iv) Calculate the congestion rent contribution (CCC_{ij}) based on (9) for all lines; v) Rank lines based on the highest value of (CCC_{ij}) and establish a priority list to reduce the solution space; vi) For each line in the priority list, run OPF with SSSC in that line and calculate the total congestion rent (TCC) based on (8); and vii) The location of the SSSC is the line whereby installing the device obtains the minimum total congestion rent (TCC).

4. EMERGENCY CONDITIONS

Congestion in a power system can occur due to several reasons such as transmission line outage, generator outage, changes in energy demand, and uncoordinated transactions. The line outage and generator outage caused by loss of excitation (LOE) are reviewed as the emergency conditions. In this section to investigate the SSSC performance on congestion management in an emergency condition.

4.1. Transmission line outage

Transmission line outages can occur due to causes such as component deterioration or adverse weather conditions. If not detected and corrected immediately, an outage could lead to critical disturbances and possibly failure in the power system. In other words, cascading transmission line outages can be lead to large blackouts. The outage of a transmission line makes overloading on some lines, and the limitation of min. or max. voltage level at load buses may be violated, or congestion occurs [31]–[36].

4.2. Generator outage

When the generator unexpectedly outages, the transmission system also will appear congested. A generator outage can happen due to the loss of excitation. The LOE is a frequent fault in synchronous machine operating, and based on the statistic; it accounts for 69% of all generator failures. The excitation source can be partially or entirely fail due to a short circuit in the field winding, accidental field breaker opening, and a breakdown in the excitation system [31], [37]–[39].

5. RESULTS AND DISCUSSION

In this study, the IEEE 14-bus system has been employed to investigate the application of an SSSC on congestion management of transmission systems in emergency conditions. The network data for analysis of the power flow and OPF are taken from MATPOWER 7.0, which is an open-source MATLAB-language M-files for solving power system simulation [40]. Also, the SSSC has been implemented in MATPOWER 7.0.

5.1. Locating an SSSC

The result of performing power flow in the base case is presented in Table 1. These results just will be used to compare the impact of the SSSC on the voltage profile and network losses. Table 2 shows the results from the OPF (LMP, and P_{ij}) and calculations performed to determine candidate transmission lines to install an SSSC. According to results, lines 1-2, 1-5, and 2-3 are three candidates for installing an SSSC, respectively.

An SSSC has been installed at the candidate lines individually, and the OPF is performed for calculating the TCC. In Figures 3(a) and (b), shows comparison the values of TCC and total generation cost without/with an SSSC. Based on the results, the transmission line 1-2 is the best location to install the SSSC, because the minimum TCC is obtained. As can be seen, the TCC and the total generation cost decrease 4.6% and 0.24%, respectively, compared with the base case. The voltage source of the SSSC has been considered $\bar{V}_s = 0.8\, p.u. \angle 3.14°$ when is placed in line 1-2. Also, the power flow results in the presence of an SSSC in transmission line 1-2 show the active power losses are 12.663 MW and the reactive power losses are 52.06 Mvar, respectively. That is means this controller can decrease network losses. In addition, the voltage amplitude remains constant, and the voltage phase angle of buses is slightly improved.

Table 1. Power flow results in the base case

	Bus number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Voltage amplitude (p.u.)	1.06	1.045	1.01	1.018	1.02	1.07	1.062	1.09	1.056	1.051	1.057	1.055	1.05	1.036
Voltage phase angle (Deg.)	0	-4.98	-12.72	-10.31	-8.77	-14.22	-13.36	-13.36	-14.94	-15.1	-14.79	-15.08	-15.16	-16.03
Network Losses	Active= 13.39 MW Reactive= 54.54 Mvar													

Table 2. OPF results in the base case and determines candidate transmission lines to install an SSSC

Bus Number	LMP ($/MWh)	Transmission Line (From Bus-To Bus)	|LMP Difference| ($/MWh)	$\|P_{ij}\|$ (MW)	CC_{ij} ($/h)	TCC ($/h)	CCC_{ij}	Priority List
1	36.724	1-2	1.636	129.67	212.14	731.068	0.243	1
2	38.36	1-5	2.937	64.66	189.906		0.2178	2
3	40.575	2-3	2.215	55.59	123.132		0.1412	3
4	40.19	2-4	1.83	48.92	89.524		0.1027	
5	39.661	2-5	1.301	37.28	48.501		0.0556	
6	39.734	3-4	0.385	11.31	4.354		0.005	
7	40.172	4-5	0.529	49.5	26.186		0.03	
8	40.17	6-11	0.421	6.09	2.564		0.0029	
9	40.166	6-12	0.645	7.65	4.934		0.0057	
10	40.318	6-13	0.841	17.12	14.398		0.0165	
11	40.155	7-9	0.006	31.34	0.188		0.0002	
12	40.379	9-10	0.152	6.49	0.986		0.0011	
13	40.575	9-14	1.031	10.2	10.516		0.0121	
14	41.197	10-11	0.163	2.54	0.414		0.0005	
		12-13	0.196	1.48	0.29		0.0003	
		13-14	0.622	4.88	3.035		0.0035	
Total generation cost= 8081.53 $/hr								

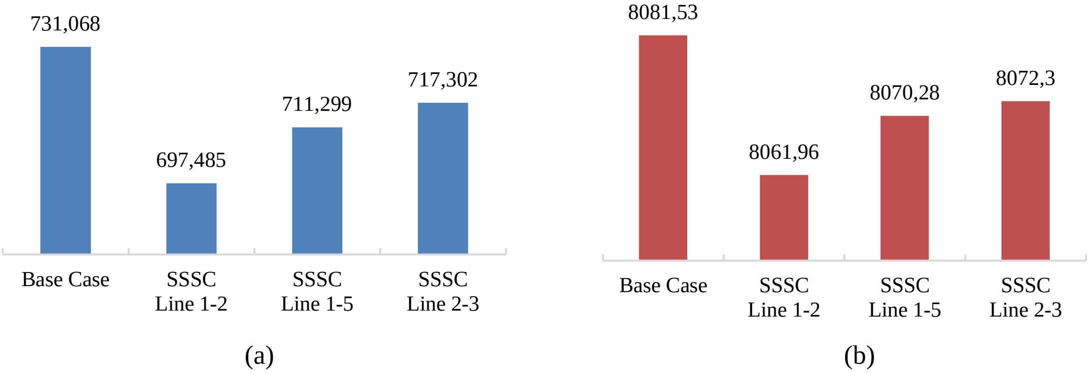

Figure 3. Comparison without/with an SSSC with (a) TCC ($/hr) and (b) Total generation cost ($/hr)

5.2. Transmission line outage

The outage of transmission line 1-5 is considered as an emergency condition to investigate the role of an SSSC on congestion management. The results of the optimal power flow and related calculations to total congestion rent after line outage are shown in Table 3. The results show the line outage causes the congestion increase so that the total congestion rent has been growth by 30.8% compared to the base case.

Table 3. OPF results and TCC after the outage of line 1-5

Bus Number	LMP ($/MWh)	Transmission Line (From Bus-To Bus)	|LMP Difference| ($/MWh)	$\|P_{ij}\|$ (MW)	CC_{ij} ($/h)	TCC ($/h)
1	35.394	1-2	2.392	178.88	427.881	955.969
2	37.786	1-5	4.837	0	0	
3	40.486	2-3	2.7	64.79	174.933	
4	40.418	2-4	2.632	63.26	166.5	
5	40.231	2-5	2.445	59.18	144.695	
6	40.214	3-4	0.068	7.01	0.477	
7	40.437	4-5	0.187	19.16	3.583	
8	40.433	6-11	0.346	5.58	1.931	
9	40.455	6-12	0.655	7.59	4.971	
10	40.645	6-13	0.839	16.86	14.146	
11	40.56	7-9	0.018	35.07	0.631	
12	40.869	9-10	0.19	6.99	1.328	
13	41.053	9-14	1.139	10.53	11.994	
14	41.594	10-11	0.085	2.04	0.173	
		12-13	0.184	1.41	0.259	
		13-14	0.541	4.56	2.467	
Total generation cost= 8260.92 $/hr						

An SSSC has been placed in transmission line 1-2 to reduce congestion, and $\bar{V}_s$ has been set at $0.8\,p.u.\angle 0°$. Table 4 shows the results of the OPF and the value of total congestion rent after the SSSC placement. Observations show that the SSSC can reduce the *TCC* by 5.8%, in other words, lead to a reduction in network congestion. Also, the total generation cost has been reduced by 37.86 $/hr.

After installing the SSSC, the network losses obtained from the power flow show the active and reactive power losses have decreased by 6.33% and 5.34%, respectively. Examination of the data shows that the SSSC has a proper performance during the line outage. It can lead to congestion management and reduce the costs of congestion and generation.

Table 4. OPF results and TCC after installing an SSSC during the outage of line 1-5

Bus Number	LMP ($/MWh	Transmission Line (From Bus-To Bus)	|LMP Difference| ($/MWh)	$\|P_{ij}\|$ (MW)	CC_{ij} ($/h)	TCC ($/h)
1	35.559	1-2	2.223	165.96	368.929	900.615
2	37.782	1-5	4.655	0	0	
3	40.466	2-3	2.684	65.74	176.446	
4	40.399	2-4	2.617	64.12	167.802	
5	40.214	2-5	2.432	60.04	146.017	
6	40.201	3-4	0.067	7.08	0.474	
7	40.418	4-5	0.185	19.24	3.559	
8	40.414	6-11	0.341	5.64	1.923	
9	40.438	6-12	0.644	7.60	4.894	
10	40.625	6-13	0.825	16.89	13.934	
11	40.542	7-9	0.02	34.74	0.695	
12	40.845	9-10	0.187	6.93	1.296	
13	41.026	9-14	1.122	10.47	11.747	
14	41.56	10-11	0.083	2.09	0.173	
		12-13	0.181	1.43	0.259	
		13-14	0.534	4.62	2.467	
Total generation cost= 8223.06 $/hr						

5.3. Generator outage

In this case, the impact of a generator outage on the congestion and role of an SSSC is investigated. It is assumed the outage occurs in the generator connected to bus #2 that can generate a maximum of 40 MW. After the outage, an SSSC with $\bar{V}_s = 0.8\,p.u.\angle -5°$ has been located in line 1-2. The total congestion rent, the total generation cost, and network losses have been analyzed in Figures 4(a)-(c), respectively. Based on the results, the SSSC reduces congestion, and hence the congestion will be managed. Besides, it can reduce the cost of generating power by generators as well as network losses.

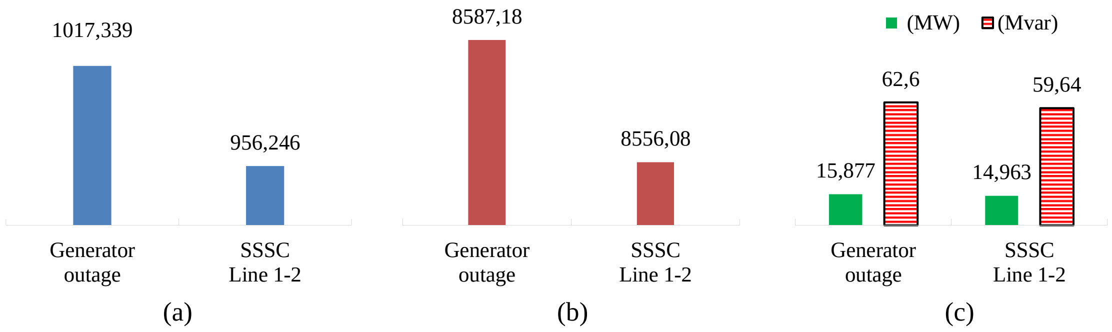

Figure 4. Results comparison without/with an SSSC after generator outage, (a) total congestion rent ($/hr), (b) total generation cost ($/hr), and (c) network losses

6. CONCLUSION

In this paper, the role of an SSSC on congestion reduction of power transmission systems in normal or emergency conditions has been presented. The SSSC is a series compensating FACTS device that can control the power flow and thus congestion management. Performed simulations on the IEEE 14-bus test system show the best location of the SSSC using the congestion rent contribution method is transmission line 1-2 aimed at congestion management. After installing the SSSC in the selected transmission line, it can be seen that the total congestion rent, the total generation cost, and network losses have been decreased. In other words, the role of the SSSC in managing the congestion by controlling the power flow is quite apparent.

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