Power System Transmission Line Overload Alleviation Using SEN Transformer

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Abstract – **Power system transmission lines are becoming more heavily loaded and this affects system security and stability. Power flow control is essential to ensure preserving lines loading security, mange the congestion of power system, alleviate line overload, and semi-equally utilize the available transmission lines as far as possible. Series connected Flexible AC Transmission Systems (FACTS) controllers help in redistributing transmission lines power flow. Among FACTS controllers, the unified power flow controller (UPFC) is the most versatile but it′s high installation and operational cost has limited it′s spread. As compared to UPFC, the newer FACTS controller SEN transformer (ST) is attractive due to its low cost and good operational characteristics. In this paper, an ST model is built in MATLAB/SIMULINK and used for alleviation of transmission line overload in a single element outage contingency case. A four bus power system is used to demonstrate the validity of the work. The simulation results show the validity of ST in maintaining system power flow security.**

Index Terms – **Components outage contingency, Overload alleviation, Power flow control, ST, UPFC.**

I. Introduction

Power systems are continuously becoming more complicated due to the steady increase of electrical energy consumption, the population increase, and the industrial development. The transmission lines which are used to transfer bulk power from generation stations to load centres are experiencing continuous loading increase.

The normal uncontrolled flow of power in transmission line is usually not the best possible. The normal flow may lead to increased losses, one line or more being overloaded while others are under loaded, operation in a state which is close to insecurity and instability, and experiencing increased voltage deviations [1]. Building of new transmission lines is not preferred for the high installation costs and many other reasons as the environmental constraints and public policies [1, 2].

The available transmission lines should be well utilized before construction of new ones [2]. A great need is arising for enhancing transmission lines capacity and controlling power flow in specific paths in addition to ensuring power system security and stability during faults and outages occurrence [3]. The role of a power flow controller (PFC) in power system network is becoming more essential. A PFC provides the ability of transmission line available transfer capability (ATC) enhancement, ensures better utilization of the available transmission lines, and helps in shifting the amount of overload of the overloaded lines to the lightly loaded ones. Fig. (1) shows a portion of a power system with a PFC.

Among FACTS controllers, the unified power flow controller (UPFC) has the ability of voltage and power flow control and the advantage of independent active and reactive power flow control [3, 4, 5-8]. SEN Transformer ST is a new emerging converter-less FACTS controller [9, 10].

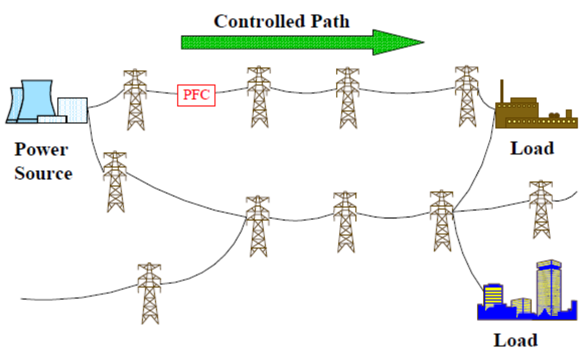

Fig. (1) Portion of a power system with a PFC

ST is a family of tap-changing transformers that has the same independent active and reactive power flow controllability of the UPFC with somehow slow response. However, for most of power system utility applications where the rapid response in the range of sub-cycle is not essential like transmission line overload alleviation, the UPFC can be replaced by ST which is economically attractive with about 20 % cost equivalent of the UPFC. ST has many technical advantages as it is less complex, has less power loss as well as less operational cost, and do not produce harmonics since it is a converter-less PFC [1, 9-12].

II. Cascade Components Outage

System components as generators, transformers, and transmission lines may be accidentally outaged due to faults or may be outaged in a programmable and planned way for maintenance. Power system components outage highly affects both configuration and operating state. A component outage may lead to one or more of the remaining components overload, and if no corrective actions are taken, a cascade outage may take place leading to partial or complete system blackout [13]. Ren and Dobson [14] have studied a nine years record of cascading transmission line outages in an electric power system with approximately 200 lines. Their study revealed that cascade failure which is the process by which initial outages of electric power transmission system components can propagate to more widespread outages and large blackouts. An initial outage weakens the system and makes further outages more likely to take place. The popular blackout happened on August 14th of the year 2003 in U.S-CANADA Power System began with a single 345 kV line outage followed by 138 kV lines as has been reported in [15].

III. Line Overload Alleviation

Transmission line overload alleviation is an essential power system practise to ensure secured and stable system operation and prevent occurrence of cascade components outage. Transmission line overload can be alleviated by lines switching, generation rescheduling, and/ or load shedding [13], or by using shunt FACTS controllers. Karithikeyan *et al*. [16] found that when a STATCOM is located at the mid of a transmission line, it enhances both voltage and power flow control. Many researchers used series FACTS controllers as TCSC, SSSC or TCPST or shunt-series FACTS as UPFC or ST [18-21, 23]. Balaraman and Kamaraj [17] stated that accurate prediction and alleviation of line overloads is the suitable corrective action to avoid network collapse due to cascade outages. In their work they have used the coded genetic algorithm to find the optimal generation rescheduling for congestion relieve. The results obtained by their method are found to be quite encouraging as compared to Simulated Annealing (SA). Sundar and Ravikumar [18] have used the TCSC to alleviate or eliminate transmission lines overloads under network contingencies. In their work, they decided the number, location and optimal setting of the TCSC parameters. Lima *et al*. [19] has optimally placed TCPS in order to put minimum number of them at selected locations so as to maximize the system loading without taking contingencies into account. Song *et al*. [20] have examined usage of different FACTS for enhancement of power system security and stated that shunt FACTS controllers are reasonable to be installed to solve voltage security problem, series FACTS controllers are reasonable to be installed for solution of power flow security problem, and the UPFC is reasonable to be installed to solve both of voltage and power flow security problems. Thukaram *et al*. [21] has optimally allocated and sized the UPFC under normal and contingency cases and vastly improved system security. As compared to power electronics based FACTS controllers, ST is economically and technically attractive. The capability of ST has been utilized for marginal prices determination and loadability enhancement in [22, 23]. Kumar and Gao [23] have shown the capability of ST in enhancing the loadability of the system and also have compared its performance with that of the UPFC.

In this paper, ST is proposed to be used to alleviate the transmission line overload in a single component outage contingency case. In this work, MATLAB/SIMULINK based ST model is built, a four bus system is modelled, and the ST model is connected to it. A generating unit outage is simulated by its circuit breaker trip. The installed meters and scopes provide the readings and curves during the simulation period (t=0-3 S) which includes the normal operation period (t=0-0.2 S), the outage period (t=0.2-3 S), and ST action period (t=2.2-3 S).

IV. Act of ST for System Control

ST with its 9 compensator windings can be used for power system voltage and independent active and reactive power flow control. Voltage can be increased, and decreased by utilization of the in-phase, and the two out-of-phase windings equally tapped respectively. Active and reactive line power flow can independently be increased or decreased by utilization of the out-of-phase windings. Many choices of limited angle ST with reduced number of windings are also available. The angle limitation limits the ability of ST voltage and power flow controllability. For the purpose of a transmission line overload alleviation by reduction of the overloaded line′s power flow, a limited angle (120^o) ST is used. The process of power flow reduction requires only operation of the compensator lagging angle windings of the limited angle ST. The process of tap-changing can be manually or automatically controlled. The manual operation of ST tap-changing may be suitable with the planned outages of components. The automatic control of tap positions is required for unexpected outages due to faults or other internal or external causes of outages. The implementation of ST tap-changing control is simpler than implementation of the UPFC control [12].

V. Application of ST in a 4-Bus System

ST, the converter-less power flow controller is a new FACTS controller that can be used effectively in transmission system to increase lines utilization and to manage their congestion by shifting the amount of the excess power of the overloaded line to the under loaded one. ST is used in this paper to alleviate the transmission line overload in case of a single component outage. A limited angle ST to compensate each phase of the transmission line with the phase lagging is modelled in MATLAB/SIMULINK so as to be used to reduce the flow of power in the overloaded line. The limited angle ST is modelled using three single phase tap-changing transformers. The mechanical tap-changing switches are modelled using timed circuit breakers. Fig. (2) shows the model of a limited angle ST (which can be used for transmission line power flow reduction since it compensates each line with a lagging voltage) and Fig. (3) shows one of the single phase tap changing transformers which represent part of the ST. The simple four bus system shown in Fig. (4) is modelled in MATLAB/SIMULINK to demonstrate the action of ST. Fig. (5) shows the four bus system MATLAB/SIMULINK model.

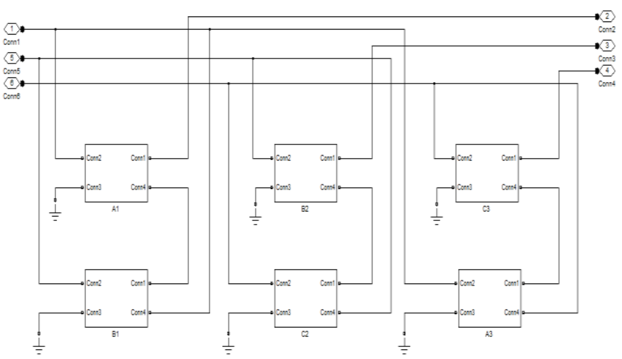

Fig. (2) A limited angle ST model

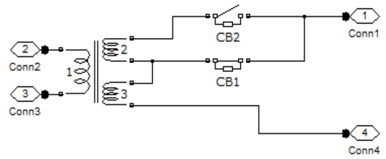

Fig. (3) Model of a tap-changing transformer as a part of ST

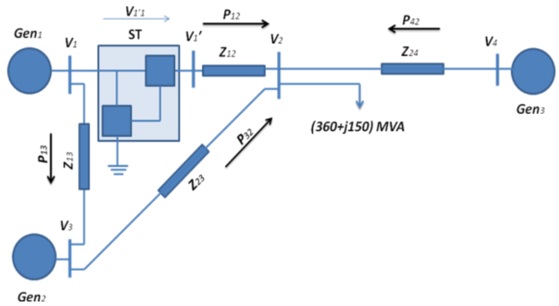

Fig. (4) Simple four bus system with ST connected

VI. The 4-Bus and ST Data

The 4 bus network generation and load, transmission lines, ST, and circuit breaker data are given in Tables (I), (II), (III) and (IV). The generation and load are in the three phase basis and the transmission lines data are per-phase. ST with its mechanical tap-changing switches takes 2 seconds to change from a tap position to the adjacent tap position [9].

TABLE I
GENERATION AND LOAD DATA

	G_1	G_2	G_3	Load (3Phase)
Voltage (LL-kV)	220	220	220	220
Angle (^{o})	0	-2	-3	P = 360 MW
R (Ω)	0.005	0.005	0.005	Q =150 Mvar

TABLE II
PER PHASE TRANSMISION LINE DATA

Fr.	To	R_1 R_o Ω/km	L_1 L_o mH/km	C_1 C_o nF/km	l (km)	P_{MAX} (MW)
1	2	R_1= 0.067 and R_o = 0.262	L_1 = 0.9613 and L_o = 3.82	C_1 = 13.06 and C_o = 5.75	60	65
1	3				80	30
2	3				100	50
2	4				40	40

TABLE III
ST DATA FOR TRANSIENT SIMULATION

Winding	V_{Ph} (kV)	R (pu)	L (pu)	Magnetization R & L (pu)	S (MVA)
Exciter	127	0.002	0.08	500, 500	750
PAR/tap	3.0	0.002	0.08		
For each regulating winding, number of taps = 2. Here only the lagging windings are operated. Tapping timing is as follows: 1st tap (CB1) operation period (t = 0 – 2.2 Sec), 2nd tap (CB2) operation period (t = 2.2 – 3.0 Sec).					

TABLE IV
CIRCUIT BREAKER DATA

The CB is firstly closed and opens to simulate G_3 outage	Opening Time (Sec)	ON state R (Ω)	OFF state R (Ω)	OFF state C (F)
	0.2	0.001	1 M	Inf.

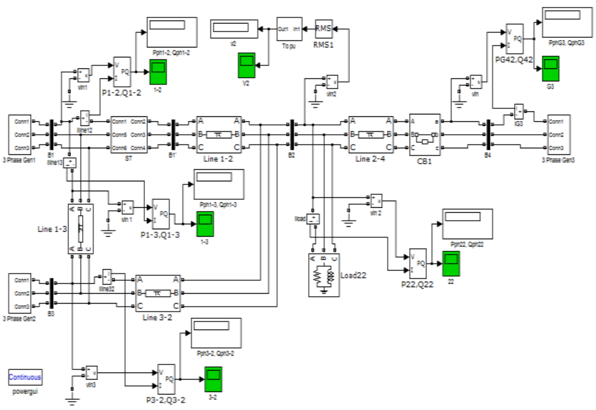

Fig. (5) The 4 bus system with ST in MATLB

VII. SIMULATION RESULTS

Readings of active and reactive power flow pre and post-outage both pre and post ST action are obtained and shown in Table (V). Also the curves of active and reactive power flow are shown in Figs. (6), (7), (8) and (9). The ST was initially operating with its first tap-position. Changing of the tap-position to the second position completely alleviated the overload.

TABLE V
LINES POWER FLOW BEFORE AND DURING THE OUTAGE PRE AND POST ST ACTION

State		Line	P_{ph} (MW)	Q_{ph} (Mvar)
Initial ST Tap Position	Before the Outage (0.0-0.2 S)	1-2	50.55	4.32
		1-3	22.32	-7.20
		3-2	24.64	7.35
		4-2	39.77	29.28
	During the Outage (0.2-2.2 S)	1-2	72.00	23.90
		1-3	22.32	-7.21
		3-2	37.84	19.08
		4-2	0.001	-0.001
Final ST Tap Position	During the Outage (2.2-3.0 S)	1-2	63.56	20.88
		1-3	22.32	-7.20
		3-2	44.75	21.56
		4-2	0.001	-0.001

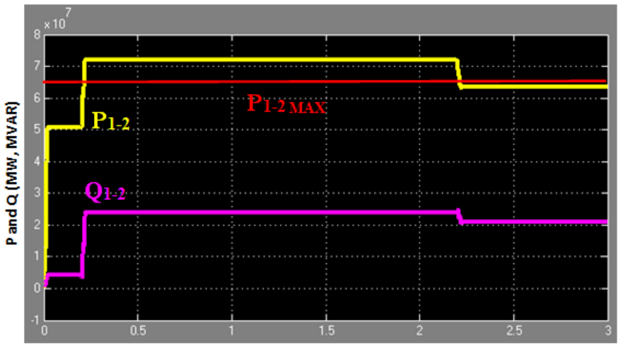

Fig. (6) Power flow $\boldsymbol{P_{12}}$, $\boldsymbol{Q_{12}}$

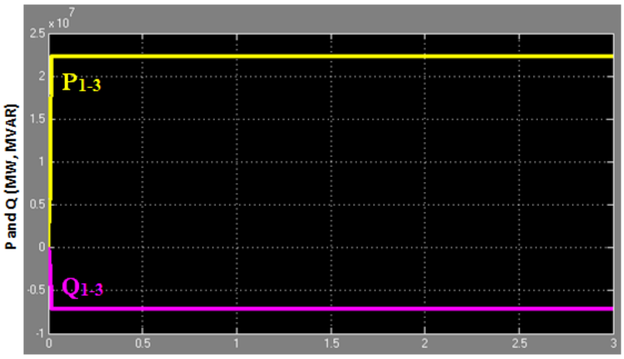

Fig. (7) Power flow $\boldsymbol{P_{13}}$, $\boldsymbol{Q_{13}}$

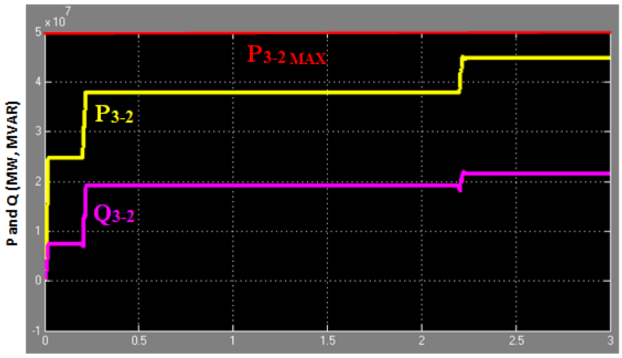

Fig. (8) Power flow $\boldsymbol{P_{32}}$, $\boldsymbol{Q_{32}}$

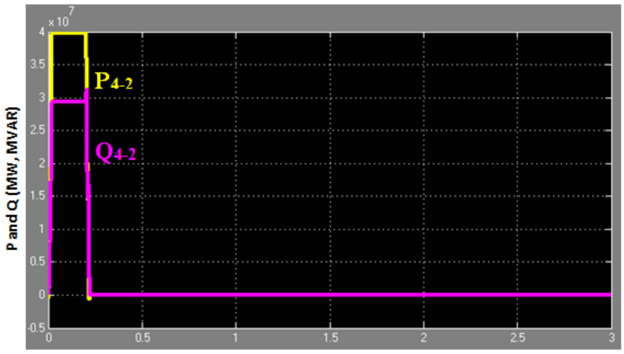

Fig. (9) Power flow $\boldsymbol{P_{42}}$, $\boldsymbol{Q_{42}}$

VIII. ST AND UPFC COMPARISON

To demonstrate the similarity of the ST and the UPFC action for transmission line overload alleviation, in this part, the ST has been used as the UPFC has been used by Othman *et. al*. [24] for transmission line overload alleviation in the IEEE-6 bus system in case of line (2-5) outage. As shown in Table (VI), both of the ST and the UPFC optimally allocated at line (1-5) alleviates line (3-5) overload. The ST which is used is a limited angle ST compensates line (1-5) with a 5 kV leading voltage which represents 0.038 of the phase voltage. Data of the IEEE-6 bus system are from [25].

TABLE VI
USAGE OF THE ST AND THE UPFC FOR LINE OVERLOAD ALLEVIATION

Line	P_{MAX} (MW)	Power Flow (MW)		
		Without Control	With UPFC [24]	With ST
3-5	20	23.97	*No Overload* (0.13, 0.876)	19.81 (0.038, 1.00)

Table (VII) presents a general comparison between the ST and the UPFC.

TABLE VII
COMPARISON OF THE ST AND THE UPFC*

Comparison Point	HN-UPFC	ST
Complexity	High	Low
Compensating at line frequency	No	Yes
Adequate response for utility power flow regulation	Yes	Yes
Compensating voltage depends on number of taps installed	No	Yes
Estimated losses at rated power	3%	<1%
Required VA rating of magnetic components (pu)	4.5	1.5
Estimated equipment cost for a unit rated 50MVA or more	7.5	1.5
Estimated losses/operating cost for a unit rated 50MVA or more	5	1

* Reference [9].

IX. DISCUSSION OF THE RESULTS

As shown in Table (V), before generator G_3 outage, all of the lines were loaded under their limits and the system was secured. Outage of generator G_3 led to line (1-2) being overloaded. It is clear that with only one tap-changing step (3 kV), an amount of (8.44 MW) power flow is shifted from the overloaded line (1-2) to the lightly loaded line (3-2) and the overload is completely alleviated.

Besides its advantages given in Table (VII), utilization of the ST in the IEEE-6 bus test system has also demonstrated the similarity of its action to that of the UPFC in alleviation of line (3-5) overload in case of line (2-5) outage as shown in Table (VI).

X. CONCLUSION

The main contributions of this work are modelling of ST and its application for transmission line overload alleviation. The simulation results have proved that ST is capable of power flow control and transmission line overload alleviation. Due to its low cost, as compared to the UPFC, ST can be more widely used in power systems for power flow control. In this paper, usage of ST improved the power system security and prevented occurrence of cascade elements outage.

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