A Comparative Study of TCSC and R-SFCL for Transient Stability Enhancement of the Nigerian 330kV Transmission Network

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***Abstract*—** The ever-increasing complexity of the Nigerian 330 kV transmission network has led to a deteriorating damping torque. The network is characterized with a high level of system instability that requires urgent control measures in order to save the system from collapse. In this paper, a comparative study of transient stability enhancement capability of Thyristor Controlled Series Compensator (TCSC) and three commercially available Resistive-type Superconductor Fault Current Limiter (R-SFCL) of different lengths based on Yttrium-Barium-Copper-Oxide (YBCO) and Bismuth-Strontium-Calcium-Copper-Oxide Coated Conductor (BSCCO) is carried out. The analysis was conducted by simulating a three-phase fault (most severe fault) on the bus with the largest load (Ikeja-West) on the network. The results obtained showed a remarkable improvement in incorporating these devices (TCSC and R-SFCLs). In all the different lengths of the categories of R-SFCL used, the BSCCO performed better than the YBCO, while the TCSC performed better than BSCCO. The result obtained can be used to predict the transient stability of the Nigerian 330 kV transmission network.

***Keywords*—** Thyristor controlled series compensator; Resistive-type superconductor fault current limiter; Complexity of power network; Nigerian 330kV transmission network; Disturbances.

1. INTRODUCTION

The complexity of an interconnected power system network due to an increased demand for energy supply has increased the system fault current level [1]. This increase in fault current level at some point exceeds the maximum short-circuits ratings of the switchgear [2]. Again, this increase in the fault current level led to a corresponding increase in the transient stability problem [3]. One of the most significant drawbacks of increasing the complexity of a transmission network is the reduction in the damping torque of the system and fall of the system voltage, which will finally lead to system collapse or blackouts as noticed in many parts of the globe [4]. Transient stability is the ability of an electric power system to regain its state of equilibrium after being subjected to a disturbance, with most of the system variables remaining intact [5]. The robustness of a power system network is determined by its critical clearing time value. The critical clearing time is the maximum allowable fault duration for the system to remain stable [6]. A larger value for critical clearing time denotes a better secured power system [7]. The Nigerian 330 kV transmission network has witnessed a series of expansions that has made the system to be more complex due

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to an increased demand for electricity. However, this expansion leads to a corresponding decrease in the damping torque. The lack of the damping torque has led to fluctuations and instability in the power system. With regard to the problem of the low damping torque which limits power transfers in transmission lines and induce stress in the mechanical shaft of machines, Power System Stabilizer (PSS) and Automatic Voltage Regulator (AVR) are widely used to enhance the system damping torque [8]. The basic function of PSS is to modulate the generator excitation to provide damping to the oscillation of the generator rotors relative to one another, while the basic function of AVR is to automatically adjust the field current of the generator in order to maintain the terminal voltage as the output varies within the continuous capability of the generator. However, due to the drawbacks of conventional PSSs and AVRs which are a large voltage profile variation under severe disturbances and negative damping torques, there is a need to find a better alternative. Therefore, this paper is aimed at investigating the use of TCSC and R-SFCL in enhancing the transient stability of the Nigerian 330 kV transmission network.

2. REVIEW OF RELATED LITERATURE

The Nigerian 330kV transmission network has been known for its usual system collapse as a result of dynamic instability that has be-deviled the network [9, 10]. Studies are still ongoing to discover new ways of improving the transient stability of the Nigerian 330 kV transmission network. Quite number of studies has been done by indigenous researchers to improve the transient stability of the Nigerian 330 kV transmission network. In [11], Static Synchronous Compensator (STATCOM) and PSS were used in damping oscillations on the North-Central network of the Nigerian 330 kV transmission network. GA and eigen values approaches were used to turn STATCOM and optimally locate PSS, respectively. The network was simulated using PSAT tool.

In [12], the transient stability enhancement capability of Unified Power Flow Controller (UPFC) in the Nigerian 330 kV transmission system was investigated. The study focused on the effect of disturbance on the largest generating unit and bus with the largest load. The results revealed that UPFC was able to increase the critical clearing time from 380 ms to 590 ms and from 470 ms to 510 ms following fault location at the largest generating unit terminal and bus with the largest load respectively.

In [13], the authors explore the use of TCSC in enhancing the transient stability of the Nigerian 330 kV transmission network. In [14, 15], the authors used Static Var Compensator (SVC) and Static Synchronous Series Controller (SSSC) to improve the dynamic responses of the Nigerian 330 kV transmission network. Their results show a remarkable improvement in damping out low oscillations in the network.

In [16], the authors used Distributed Static Series Compensator (DSSC) to improve the transient stability of two machine power systems along with PSS as a supplementary controller.

In [17], the authors used SVC and PSS to improve the transient stability of a power network. Their results show a remarkable performance with both devices.

The authors in [18] investigated the power system angular stability as affected by reduced inertia due to wind displacing synchronous generators. Their results show that the effect of reduced inertia due to the wind displacing synchronous generators is different as the location of displacement changes. In this paper, a comparative assessment of the use of TCSC and R-SFCL in enhancing the transient stability of the Nigerian 330kV transmission network will be investigated for an improved system performance.

3. STUDY SYSTEM

In this paper, the single-line diagram of the Nigerian 330 kV transmission network used as a test system is as shown in Fig. 1. It comprises eleven generators, thirty six transmission lines and twenty one load buses. The swing generator is the largest generator (Egbin); and the fault location is the bus with the largest load (Ikeja-West). From Fig. 1, there are seven lines that could cause disturbance on the largest bus this Ikeja West-Egbin, Ikeja West-Benin, Ikeja West-Akangba, Ikeja West-Sakete, Ikeja West-Olorunsogo GS, Ikeja West-Omotosho and Ikeja West-Oshogbo.

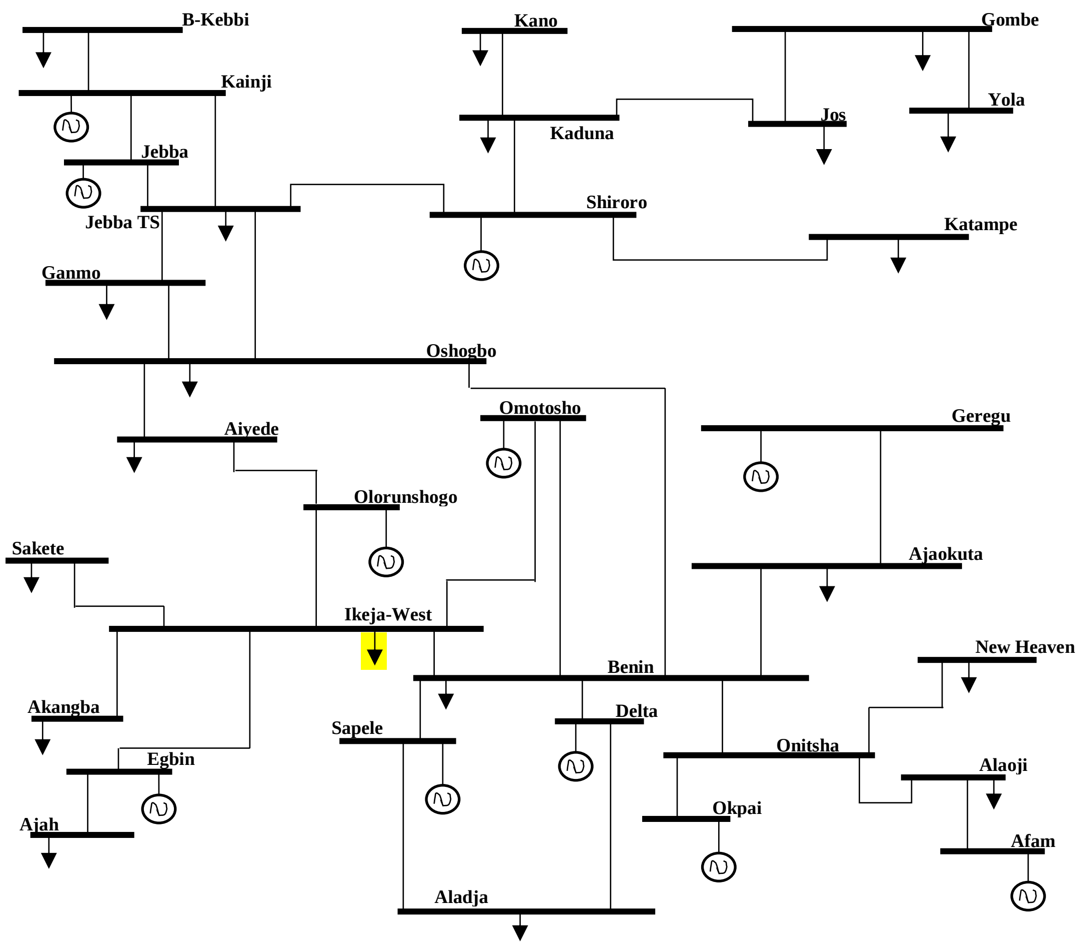

Fig. 1. Single line diagram of the Nigerian 330 kV transmission network.

Table 1: Maximum and minimum power generation limit.

Bus No	Bus name	P_{max} [MW]	Q_{max} [MW]	Q_{min} [MW]
1	Egbin G.S	Slack Bus	Slack Bus	Slack Bus
7	Olorunshogo G.S	335	184	-120
8	Omotosho G.S	335	184	-120
11	Shiroro G.S	600	316	-60
13	Jebba G.S	590	284.4	-180
15	Kainji G.S	760	246.8	-240
23	Geregu G.S	414	255	-135
27	Sapele G.S	960	523	-300
28	Delta G.S	900	504	-288
29	Okpai G.S	480	238.8	-150
30	Afam G.S	681	648	-390

Table 2: Maximum and minimum load demands.

Bus No	Bus name	Maximum load demand		Minimum load demand	
		[MW]	[Mvar]	[MW]	[Mvar]
2	Benin	298	144(+75)	188	91
3	Ikeja West	510	246(+75)	321	155
4	Akangba	471	228	297	144
5	Sakete	145	70	91	44
6	Aiyede	270	130	170	82
9	Oshogbo	235	114(+75)	148	72
10	Ganmo	270	130	170	82
12	Jebba T.S	412	199(+150)	260	125
14	Birnin Kebbi	112	54(+30)	71	34
16	Kano	250	121(+75)	157	76
17	Kaduna	275	133(+75)	173	84
18	Jos	141	68	89	43
19	Gombe	180	87(+100)	113	55
20	Yola	112	54	71	34
21	Katampe	300	127	189	62
22	Ajaokuta	96	46	60	29
24	Onitsha	162	76	102	48
25	Alaoji	266	124	167	78
26	New Haven	235	110	148	69
31	Aja	220	103	139	65
32	Aladja	167	81	105	51

Table 3: Transmission line parameters.

No	Transmission line		Length	Impedance		Shunt admittance
	From	To	L [km]	Resistance [Rpu]	Inductance [Xpu]	1/2 Bpu [S]
1	Egbin G.S	Ikeja West	62	0.001122	0.008625	0.064345
2	Egbin G.S	Aja	14	0.000253	0.001948	0.014529
3	Benin	Ikeja West	280	0.005065	0.038953	0.290589
4	Benin	Omotosho G.S	51	0.001826	0.015501	0.096916
5	Benin	Oshogbo	251	0.008989	0.076291	0.476977
6	Benin	Ajaokuta	195	0.003492	0.029635	0.18528
7	Benin	Onitsha	137	0.002453	0.02082	0.130171
8	Benin	Sapele G.S	50	0.000904	0.006956	0.051891
9	Benin	Delta G.S	41	0.001468	0.012462	0.077913
10	Ikeja West	Akangba	17	0.000304	0.002584	0.016`53
11	Ikeja West	Sakete	70	0.002507	0.021276	0.133021
12	Ikeja West	Olorunshogo G.S	30	0.001074	0.009118	0.057009
13	Ikeja West	Omotosho G.S	200	0.007163	0.06079	0.380061
14	Ikeja West	Oshogbo	250	0.008953	0.075987	0.475077
15	Aiyede	Olorunshogo G.S	60	0.002149	0.018237	0.114018
16	Aiyede	Oshogbo	115	0.004118	0.034954	0.218535
17	Oshogbo	Ganmo	75	0.002686	0.022796	0.142523
18	Oshogbo	Jebba T.S	157	0.002811	0.02386	0.149174
19	Ganmo	Jebba T.S	80	0.002865	0.024316	0.152025
20	Shiroro	Jebba T.S	244	0.004369	0.037082	0.231837
21	Shiroro	Kaduna	96	0.001719	0.01459	0.091215
22	Shiroro	Katampe	218	0.003944	0.030328	0.226244
23	Jebba T.S	Jebba G.S	8	0.000145	0.001113	0.008303
24	Jebba T.S	Kainji G.S	81	0.00145	0.01231	0.076962
25	Birnin Kebbi	Kainji G.S	310	0.005551	0.047112	0.589095
26	Kano	Kaduna	230	0.004118	0.034954	0.43707
27	Kaduna	Jos	196	0.00351	0.029787	0.37246
28	Jos	Gombe	264	0.004727	0.040121	0.501681
29	Gombe	Yola	240	0.004298	0.036474	0.456074
30	Ajaokua	Geregu G.S	1	0.000018	0.000139	0.001038
31	Onitsha	Alaoji	138	0.004942	0.041945	0.262242
32	Onitsha	New Haven	96	0.003438	0.029179	0.182429
33	Onitsha	Okpai G.S	60	0.001085	0.008347	0.062269
34	Alaoji	Afam G.S	25	0.000452	0.003478	0.025945
35	Sapele G.S	Aladja	63	0.002256	0.019149	0.119719
36	Delta G.S	Aladja	32	0.001146	0.009726	0.06081

4. MATHEMATICAL MODELING

4.1. Modeling of Swing Equation

For a power system network with 'm' generators, the internal voltage can be determined using Eq. (1):

$$E_i = V_i + jx_{di}\left[\frac{P_{gi}-jQ_{gi}}{V_i^*}\right] = E_i\angle\delta_i \tag{1}$$

where E_i is the internal voltage of the machine; V_i is the terminal voltage; x_{di} is the impedance of the machine; P_{gi} and Q_{gi} are the real and reactive power of the machine, respectively.

Loads are converted to equivalent admittance using Eq. (2):

$$y_{id} = \frac{P_{di}-jQ_{di}}{|V_i|^2} \text{ for } i = 1,2,\ldots,m \tag{2}$$

where P_{di} and Q_{di} are the respective equivalent real and reactive powers at each load bus.

The pre-fault bus admittance matrix $[Y_{bus}]$ is formed as given in Eq. (3):

$$Y_{bus} = \begin{bmatrix} Y_{mm} & Y_{mn} \\ Y_{nm} & Y_{nn} \end{bmatrix} \tag{3}$$

where Y_{mm} is a sub matrix of dimension [m x m]. It corresponds to the buses where generators are connected. Y_{mn}, Y_{nm} and Y_{nn} are other sub matrixes.

Using the Kron's reduction method is given by

$$Y_{ij(new)} = Y_{ij(old)} - \frac{Y_{ik(old)}Y_{kj(old)}}{Y_{kk}} \tag{4}$$

where node k is to be eliminated. Eq. (3) can be reduced to

$$Y_{bus(reduced)} = Y_{mm} - Y_{mn}Y_{nn}^{-1}Y_{nm} \tag{5}$$

The electrical power output of the generator is given as

$$P_{ei} = |E_i|^2 Y_{ii}\cos\theta_{ii} + \sum_{j=1}^{m}|E_i||E_j||Y_{ij}|\cos(\theta_{ij}-\delta_i+\delta_j) \tag{6}$$

for i = 1, 2, …, m, the rotor dynamics is given by

$$\frac{H_i}{\pi f_0}\frac{d^2\delta_i}{dt^2} = P_{mi} - P_{ei} \tag{7}$$

where H is the inertia constant; f_0 is the frequency; and P_{mi} is the mechanical input power.

The solution of the swing equation is obtained by using a numerical solver "ODE45" in MATLAB Software.

4.2. Modeling of TCSC

TCSC is one of the best flexible AC transmission systems devices used to increase power transfer and improve power system stability [15]. The TCSC is a series type reactive compensator, which comprises three main components: Capacitor bank (c), bypass inductor (L) and bidirectional thyristors SCR_1 and SCR_2. The reactance of TCSC (X_{TCSC}) is adjusted by controlling the firing angle (α). Fig. 2 shows the basic diagram of TCSC.

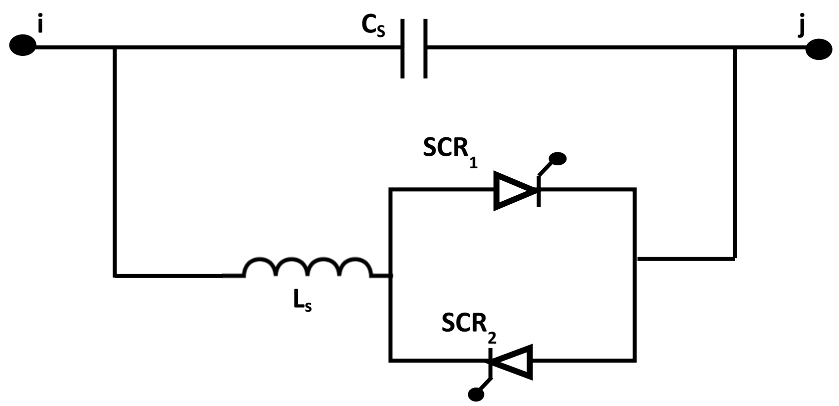

Fig. 2. Basic circuit diagram of TCSC [15].

The TCSC can be controlled to function either in the capacitive or inductive mode to avoid steady state resonance as shown in Fig. 3 [15].

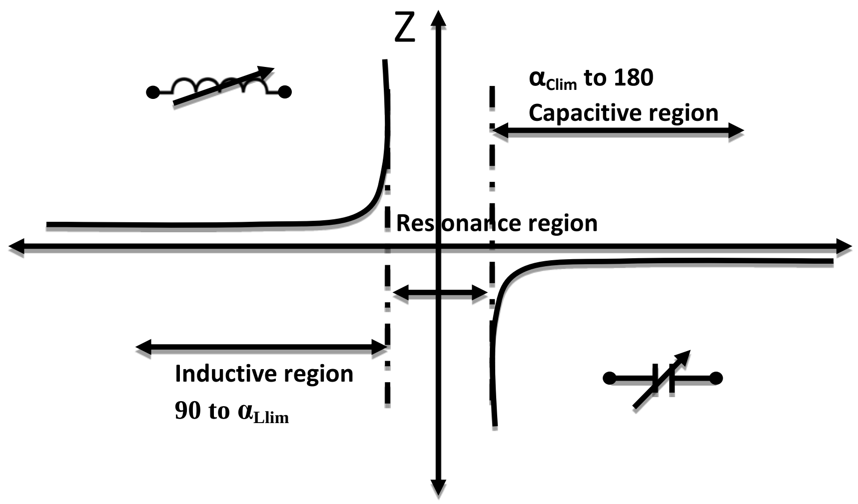

Fig. 3. Impedance characteristics of TCSC.

There is a relationship between the firing angle (α) and the reactance (X_{TCSC}) of a TCSC as described by Eq. (8) [19]:

$$X_{TCSC}^{(\alpha)} = X_c - \frac{X_c^2}{(X_c - X_p)} * \frac{\sigma + Sin\sigma}{\pi} + \frac{4X_c^2}{(X_c - X_p)} * \frac{Cos^2(\sigma/2)}{(K^2 - 1)} * \frac{(K \cdot \tan(K\sigma/2) - \tan(\sigma/2)}{\pi} \quad (8)$$

where X_C is capacitance of the capacitor; X_P is the inductive reactance of the reactor; σ = 2 (π-α)- the conduction angle of TCSC controller; K= $\sqrt{\frac{X_c}{X_p}}$ - the compensation ratio.

The TCSC is operated here in the capacitive mode for transient stability enhancement [13]. In this research work, the transmission line reactance where TCSC is to be placed was adjusted directly by the reactance of TCSC (X_{TCSC}).

From a modeling point of view, the value of X_{TCSC} is a function of the transmission line reactance where TCSC is located such that:

$$X_{line(new)} = X_{line(old)} + X_{TCSC} \tag{9}$$

$$X_{TCSC} = r_{TCSC} * X_{line} \tag{10}$$

where $X_{line\ (new)}$ is line reactance after compensation; $X_{line(old)}$ is the line reactance before compensation; r_{TCSC} is the compensation factor.

In order to avoid overcompensation of the transmission line, r_{TCSC} is chosen as in Eq. (11) [20]:

$$0.7X_{line} \geq r_{TCSC} \geq 0.2X_{line} \tag{11}$$

4.3. Modeling of R-SFCL

The R-SFCL is the simplest type of SFCL due to its High Temperature Superconductor (HTS) inherent characteristics [21]. The current limiting component of SFCL consists of HTS, which maybe in the form of a tape, wire, or bulk material that provides a pathway for the current to flow [22]. Under a normal condition, the SFCL is in its superconducting state; and the resistance is zero. When the fault occurs, the current increases and makes the superconductor to quench, thereby making its resistance increase exponentially as shown in Fig. 4.

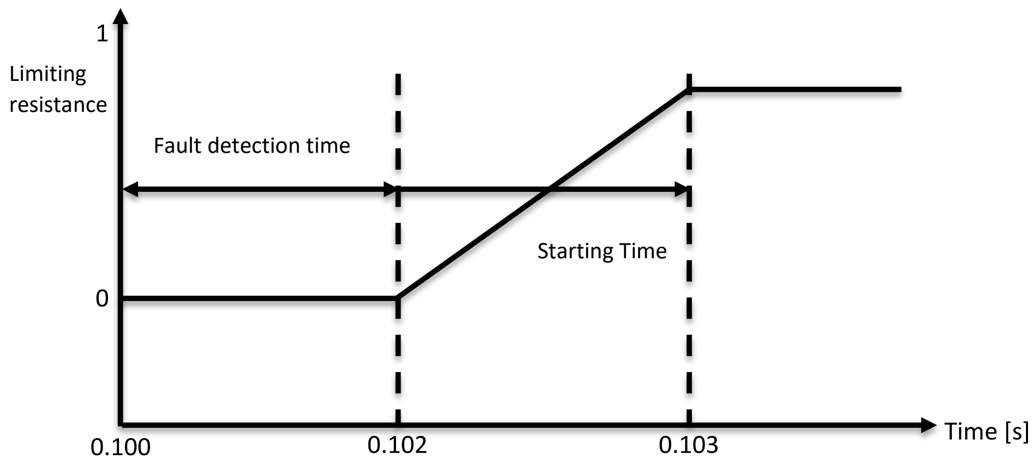

Fig. 4. FCL characteristics.

The resistance of SFCL with respect to time (t) is given by Eq. (12) [23].

$$R_{SFCL} = \begin{cases} 0 & t_o > t \\ R_m\left[1 - \exp\left(-\dfrac{t - t_o}{T_{sc}}\right)\right]^{\frac{1}{2}}, & t_o \leq t < t_2 \\ a_1(t - t_1) + b_1, & t_1 \leq t < t_2 \\ a_2(t - t_2) + b_2, & t_2 \leq t \end{cases} \tag{12}$$

where R_m represents the maximum resistance in the quenching state; T_{sc} is the time constant of the SFCL during transition from the superconducting state to the normal conducting state; t_0 is the time to start the quenching; t_1 and t_2 are the first and second recovery times respectively. After the recovery of fault, the resistance goes back to zero.

In this study, three commercially available R-SFCLs are used for this simulation. One of them is coated tapes manufactured by Super-Power Inc. (SCS12050 and SF12100). The values of the three R-SFCLs resistances used in this research are presented in Table 4.

Table 4: Resistive-type SFCLS of different lengths [24].

Length [m]	Material	Resistance of HTS [Ω]	Temperature [K]
70	BSCCO	7.1308	151.71
	SCS12050	7.4182	210.77
	SF12100	7.6056	286.84
80	BSCCO	8.0605	138.15
	SCS12050	8.3537	183.33
	SF12100	8.5658	241.97
100	BSCCO	8.7539	121.75
	SCS12050	10.2135	150.85
	SF12100	10.4791	188.58
120	BSCCO	9.3677	111.43
	SCS12050	12.0726	133.29
	SF12100	12.3268	159.21

In this research work, the location of TCSC and R-SFCL are chosen such that it will improve the transient stability of the most severely disturbed generator. The devices are placed between the line connecting Alaoji bus and Afam bus. Details of the most severely disturbed generator can be found in [25].

5. RESULT AND DISCUSSION

In order to determine the transient stability improvement capability of TCSC and the three commercially coated conductors of SFCLs (BSCCO, SCS12050 and SF12100), a 3-phase fault (most severe fault) was created on the bus with the largest load (Ikeja-West); and the most severely disturbed generator (Afam generator) was considered for transient stability enhancement. Figs. 5-8 show the responses of the generator with TCSC and the three R-SFCLs of different lengths, ranging from 70 m to 120 m.

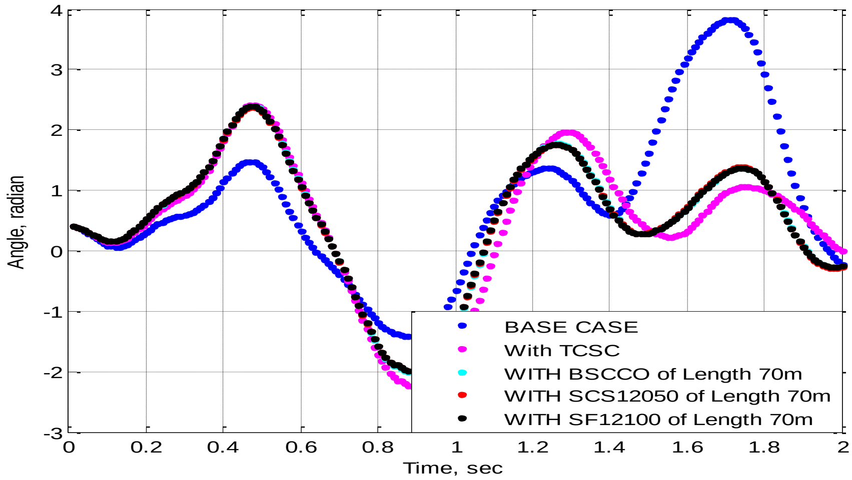

Fig. 5. Swing curves of the generator with 70 m long R-SFCL.

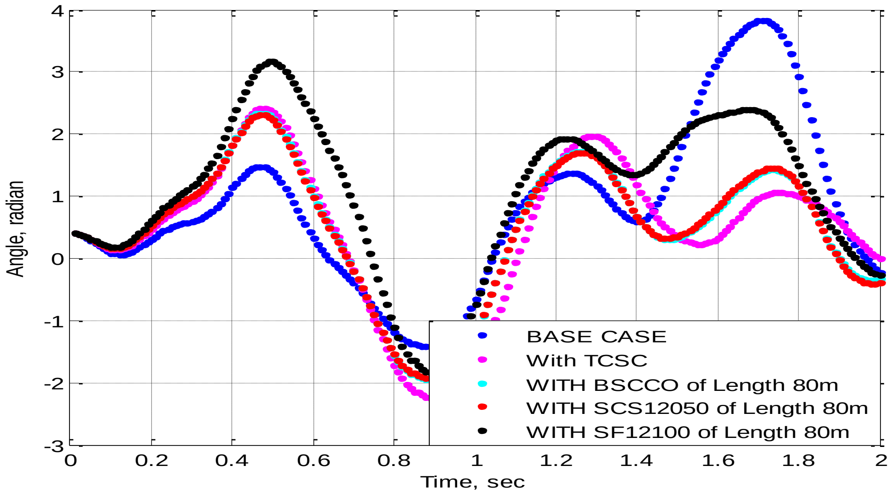

Fig. 6. Swing curves of the generator with 80 m long R-SFCL.

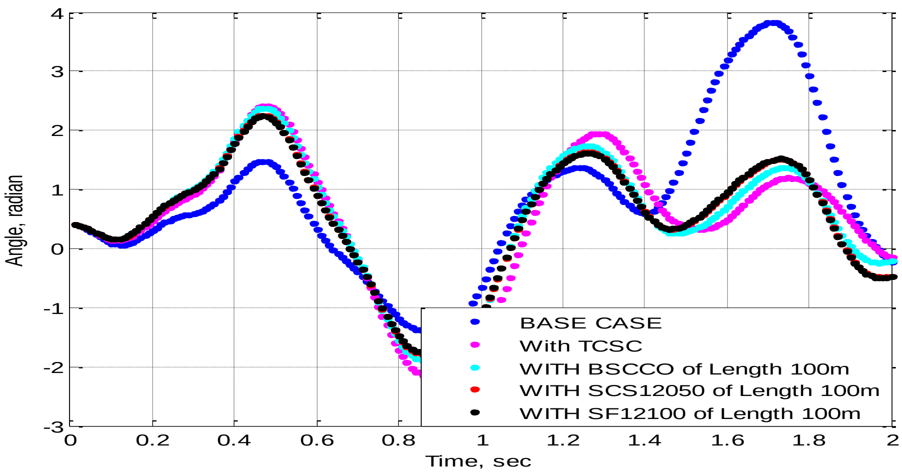

Fig. 7. Swing curves of a generator with 100 m long R-SFCL.

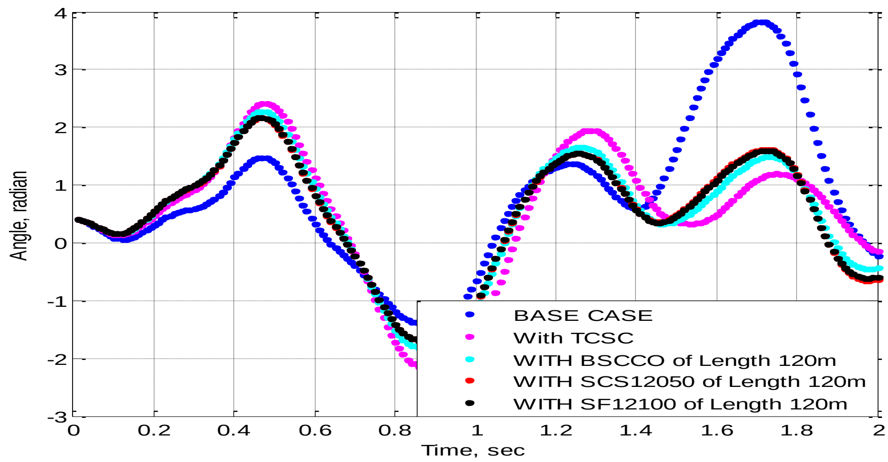

Fig. 8. Swing curves of a generator with 120 m long R-SFCL.

Fig. 5 shows the dynamic responses of the generator with TCSC and the three commercially coated conductors of length 70m. TCSC shows a better performance in damping low frequency oscillation than the three R-SFCLs of length 70 m. Figs. 6 and 7 illustrate the dynamic responses of the generator with TCSC and the coated conductors of length 80 m and 100 m. Again, the TCSC displayed a better performance than the three commercially coated conductors of length 80 m and 100 m, followed by BSCCO, SCS12050, and SF12100 respectively. Lastly, Fig. 8 depicts the responses using TCSC and the coated conductors of length 120 m. Also, TCSC performed better than three commercially coated conductors of length 120 m. Table 5 shows the summary of a transient stability improvement for different lengths of R-SFCLs based on YBCO and BSCCO and TCSC at 1.7 s which correspond to the amplitude of the last cycle of the rotor angle.

Table 5: Summary of percentage improvement of transient stability assessment.

Length [m]	Material	Improvement of transient stability [%]
70	BSCCO	71.14
	SCS12050	70.76
	SF12100	70.97
80	BSCCO	69.50
	SCS12050	68.59
	SF12100	41.78
100	BSCCO	70.88
	SCS12050	66.55
	SF12100	66.21
120	BSCCO	67.30
	SCS12050	63.65
	SF12100	64.27
	TCSC	77.77

In all the various lengths of R-SFCLs used, BSCCO performed better than YBCO, while the TCSC performed better than the BSCCO. The results obtained showed a remarkable transient stability improvement of the Nigerian 330 kV transmission network.

6. CONCLUSIONS

In this paper, comparing the transient stability improvement capability of TCSC and three commercially available R-SFCLs of different lengths was carried out. The test case was the Nigerian 330 kV transmission network. The time domain simulation was done using MATLAB in the event of a major disturbance like a 3-phase fault. The results obtained showed the effectiveness of using TCSC of different lengths in damping out low frequency oscillation. The TCSC showed a better performance compared to the different R-SFCLs of different lengths used. This study will be useful to the Transmission Company of Nigeria for effective planning of the Nigerian 330 kV transmission network in order to solve the problem of an already stressed network due to its complexity, problem of varying loads, etc.

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