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Transient Stability Improvement using Resistive-type Superconducting Fault Current Limiters (R-SFCL)

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Abstract - The rapid growth in the demand for electrical energy due to the astronomic growth in population has led to increase in the system fault current levels. This increase in fault current if not properly checked, could lead to system collapse. Superconducting Fault Current Limiters (SFCLs) are used in power system networks to mitigate against high fault current levels. In this study, the transient stability enhancement capability of three commercially available Resistive-type Superconducting Fault Current Limiters (R-SFCLs) based on Yttrium-Barium-Copper-Oxide (YBCO) and Bismuth-Strontium-Calcium-Copper-Oxide (BSCCO) Coated Conductors of different lengths were simulated. The test case was the Nigeria 330-kV transmission network. The Runge-Kutta method was used to solve the differential equations characterizing the swing equations of the generators. The location of the SFCL was chosen such that the transient stability of the most severely disturbed generator will be improved. The result of the outcome of the SFCL shows a remarkable improvement in the transient stability of the transmission network.

Keywords - Transient stability; superconducting fault current limiter; Nigeria 330-kV transmission; Swing equation; Resistive type superconductor; Multi-machine power systems

I. INTRODUCTION

Due to increased population and other technological advancements, the power system network has become more complex in order to accommodate the growth of electric power demand. As an effect, the fault current becomes high and transient stability problem becomes more severe [1]. This increase in fault current at some point may exceed the maximum short-circuit ratings of the switchgear and other equipment [2]. As a consequence, in order to maintain stability of the system, replacement of switchgear or reconfiguration of the system will be needed, which ultimately will lead to some problems like high cost, increased power loss, decreased operational reliability, etc. [3]. To overcome this high fault current, traditional means have been applied in the past, such as the use of Current-limiting fuses, high impedance transformers, series reactors, etc. which ultimately reduces the fault current in the system [4].

Superconductor Fault Current Limiter (SFCL) is a dependable alternative to the aforementioned conventional devices in reducing the fault current of a transmission system at the occurrence of a disturbance [5]. Also, SFCL ensures the enhancement of transient stability by reducing the fault current in a more efficient and rapid manner [6]. An SFCL helps but does not completely suppress the fault current, but rather reduces it to a level that the equipment can withstand. There are two basic types of SFCLs: The Resistive-type SFCL and Inductive-type SFCL [7]. The resistive-type superconductor fault current limiter (R-SFCL) is inserted directly with the line to be protected, while the inductive-type superconductor fault current limiter (I-SFCL) is a transformer shunted by a superconducting tube [8]. The R-SFCL has the advantage of instantaneous limiting of fault current, zero resistance at normal operating conditions and automatic response without any external device over I-SFCL.

Over the last decade, different studies have been done in the area of transient stability enhancement using SFCLs. The authors in [9] did a comparative study between the impacts of installing R-SFCL and I-SFCL with YBCO and Bi-2212 materials on the transient stability of a Multi-Machine power system. The result shows improvement with both R-SFCL and I-SFCL, but with R-SFCL performing better than I-SFCL. In [10], the authors carried out a study to determine the optimal resistive value of an R-SFCL using eigenvalue analysis. The result reveals that the optimized SFCL improves the damping performance of the Multi-Machine power system. The authors in [11] presented a comparative study of resistive and inductive SFCLs from current limitation and power system stability point of view. The result also shows better performance of the resistive-type than inductive-type. In [12], the authors determined the optimal resistive value of an R-SFCL by analyzing the transient stability based on equal-area criterion. The simulation result proves the effectiveness of the proposed model.

Most of the aforementioned studies are either concerned with either transient stability enhancement using R-SFCL or I-SFCL without considering the length of the SFCL. This paper aimed at enhancing the transient stability of the Nigerian 330-kV transmission network using Resistive-type Superconductor Fault Current limiting coated conductors of different lengths. In this way the transient stability of the network is improved, challenging the need for the replacement of switchgear or reconfiguration of the network. The result obtained in this study would be useful for system planners in the subsequent expansion of the Nigeria 330-kV transmission network. Section 2 of this paper described the case study transmission network. Section 3 presents the methodology section, while section 4 gives the results of the analysis and discusses the results. Finally, section 5 summaries the conclusions obtained from the study.

II. THE NIGERIAN 330-kV TRANSMISSION NETWORK

Figure 1 depicts the single line diagram of the Nigerian 330-kV Transmission network used in this study. It consists of 11 generating stations, 21 load buses, 36 transmission lines and 32 buses. The total installed capacity is approximately 5,000MW with 5,524km lines. For this case study, the buses are specified and identified as shown in Table 1. The transmission lines and power plants are described in Table 2 and 3 respectively.

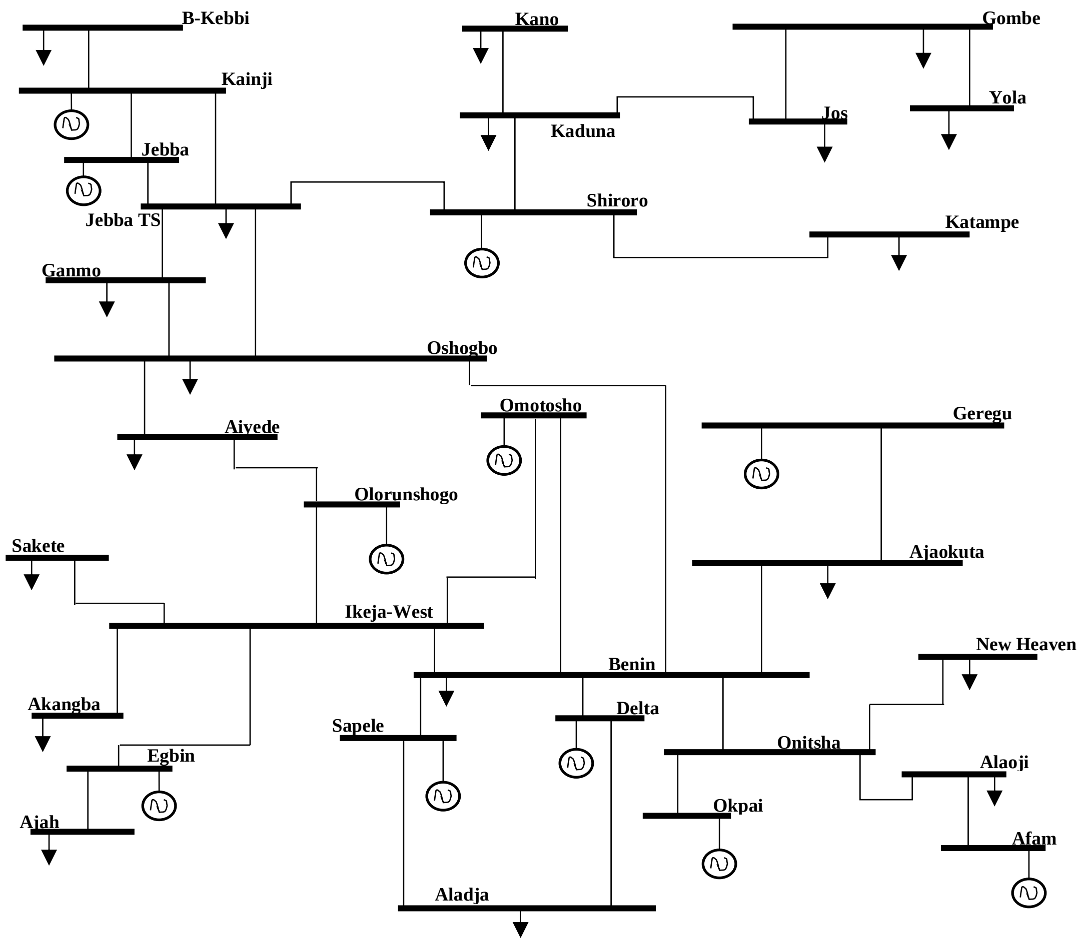

Figure 1: Single Line Diagram of the Nigerian 330-kV transmission

Table 1: Bus nomenclature

Bus No	Bus Name	Bus No	Bus Name
1	Egbin G.S	17	Kaduna
2	Benin	18	Jos
3	Ikeja West	19	Gombe
4	Akangba	20	Yola
5	Sakete	21	Katampe
6	Aiyede	22	Ajaokuta
7	Olorunshogo G.S	23	Geregu G.S
8	Omotosho G.S	24	Onitsha
9	Oshogbo	25	Alaoji
10	Ganmo	26	New Haven
11	Shiroro G.S	27	Sapele G.s
12	Jebba T.S	28	Delta G.S
13	Jebba G.S	29	Okpai G.S
14	Birnin Kebbi	30	Afam G.S
15	Kainji G.S	31	Aja
16	Kano	32	Aladja

Table 2: Nigerian 330-kV Transmission Line Parameters

S/N	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	*Ajaokuta*	*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

III. MATERIALS AND METHODS

3.1 Mathematical Model of Multi-Machine Power System

The dynamics of a multi-machine power system is governed by the non-linear differential equation in Eqn. (1):

$$M_k \frac{d^2\delta_k}{dt^2} = P_{mi} - P_{ei} \qquad k = 1, \ldots n \tag{1}$$

where, M = angular momentum (J-sec/rad); P_m= shaft power input (W); P_e= electrical power output (W); δ= angular displacement (rad.)

The electrical power output of each generator is given by Eqn. 2:

$$P_{ek} = E_k^2 Y_{kk} \cos\theta_{kk} + \sum_{k=1}^{m} |E_k||E_j||Y_{kj}| Cos(\theta_{kj} - \delta_k + \delta_j) \tag{2}$$

The rotor dynamics representing the swing equation of generator k is given by Eqn. (3)

$$\frac{H_k}{\pi f_o}\frac{d^2\delta_k}{dt^2} = P_{mk} - P_{ek} \tag{3}$$

where, H= Inertia Constant (MJ/MVA); δ= angular displacement (radian); P_m=mechanical power input (W); P_e=electrical power input (W); E=internal voltage (V); Y=admittance; F=frequency (Hz). (Every other symbol has their usual meaning).

A program involving time-domain simulation like step-by-step integration, modified Euler method, Runge-Kutta method, etc. can be used to solve these differential equations by producing state variables with time response. In this paper, Runge-Kutta iteration method is used in solving the differential equations. The swing curves generated is used in determining the Generator stability.

3.2 Mathematical Modelling of Resistive-type SFCL

The Resistive-type SFCL is considered because of its simple design, lightness and smaller size when compared with inductive-type SFCL. It consists of a series *n*-numbers of resistance as shown in Figure 2. Each unit consists of a stabilizer resistance R_{sr}, superconductor resistance R_{cr} connected in parallel with R_{sr} and the coil inductance L_n.

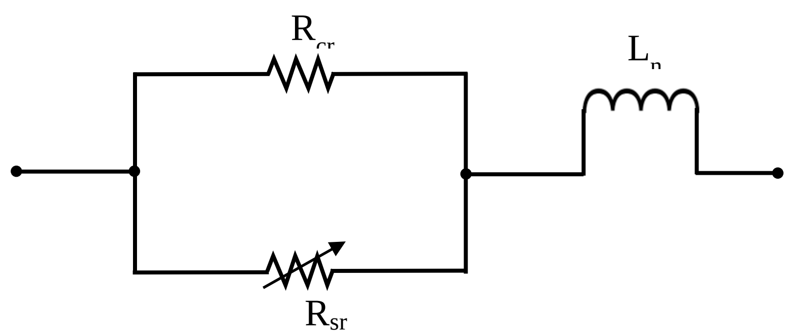

Figure 2: Structure of a Resistive-type SFCL unit

The value of R_{cr} and R_{sr} are both zero during normal operation of the system. The resistance of SFCL with respect to time (t) is given by Eqn. 4 [13].

$$R_{SFCL} = \begin{cases} 0 & t_o > t \\ R_m\left[1-\exp\left(-\dfrac{t-t_o}{T_{sc}}\right)\right]^{\frac{1}{2}}, & t_o \le t < t_2 \\ a_1(t-t_1)+b_1, & t_1 \le t < t_2 \\ a_2(t-t_2)+b_2, & t_2 \le t \end{cases} \tag{4}$$

where R_m represents the maximum resistance in the quenching state; T_{sc} is the time constant of the SFCL during transition from superconducting state to normal conducting state; t_0 is the time to start the quenching. Also, t_1 and t_2 are the first and second recovery times respectively. After the recovery of fault, the resistance again 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 In. (SCS12050 and SF12100). The values of the resistances of the three R-SFCLs used are presented in Table 3.

Table 3: Resistive-Type SFCLs of different Lengths [14]

Length (m)	Material	R_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

The location of the R-SFCL is chosen such that the stability of the severely disturbed generator is improved.

IV. RESULTS AND DISCUSSION

4.1 Case 1: Base Case Scenario

In this scenario, a three-phase fault was created on bus-6. Figures 3 and 4 show the dynamics of the generators, with the generator at Afam power station mostly or severely disturbed. At a CCT of 840-ms (Figure 3), the system was still stable, but at a CCT of 850-ms (Figure 4), the generator at Afam station lost synchronism. Hence, when a 3-phase fault occurs on bus-6, the fault must be cleared at a CCT of 840-ms for the system to remain stable.

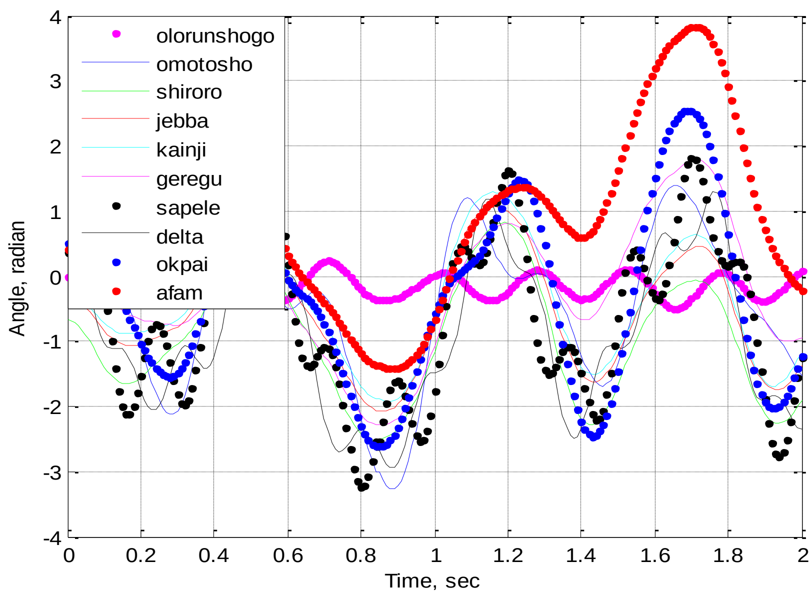

Figure 3: Rotor angle for a Three-phase fault on Bus 6, with Line 16-2 Removed (CCT = 840-ms)

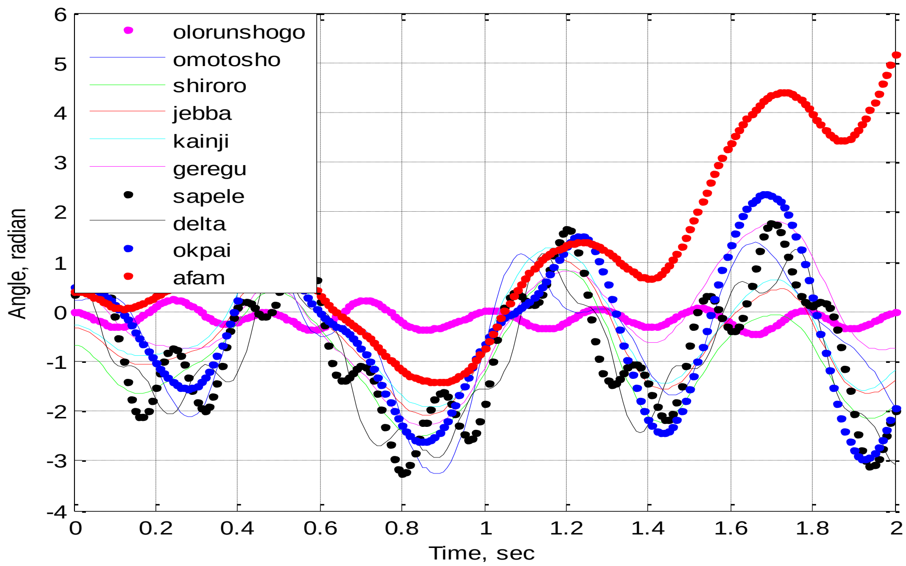

Figure 4: Rotor angle for a Three-phase fault on Bus 6, with Line 16-2 Removed (CCT = 850-ms)

4.2 Case 2: With BSCCO Coated Conductor

In this scenario, the dynamic response of the generator at Afam power station is assessed with the incorporation of an R-SFCL with BSCCO Coated Conductor of different lengths between bus-25 and bus-30 at a CCT of 850-ms. Figure 5 shows the response without R-SFCL and with R-SFCL at a CCT of 850-ms. The incorporation of BSCCO Coated Conductor of different lengths was able to maintain stability.

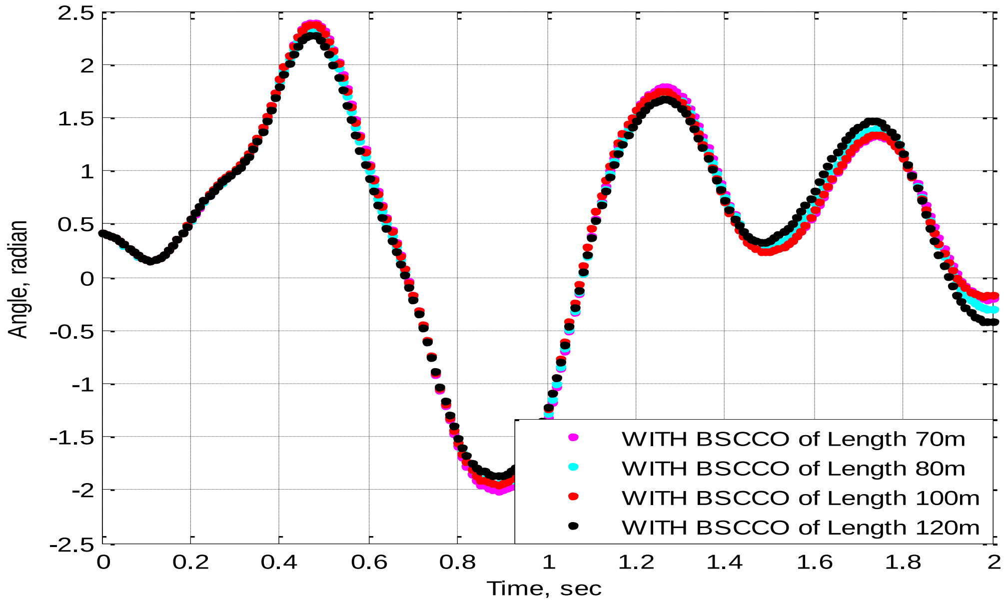

Figure 5: Swing curve of generator at Afam For BSCCO of different Lengths (CCT = 850ms)

4.3 Case 3: With SCS12050 Coated Conductor

Figure 6 shows the dynamic responses of the generator at Afam power station at a CCT of 850-ms when a 3-phase fault occurs on bus-6. It was observed that the generator that lost synchronism at a CCT of 850-ms without R-SFCL, was now able to maintain synchronism at 850-ms with the incorporation of an R-SFCL with SCS12050 coated conductor of different lengths between Alaoji and Afam buses.

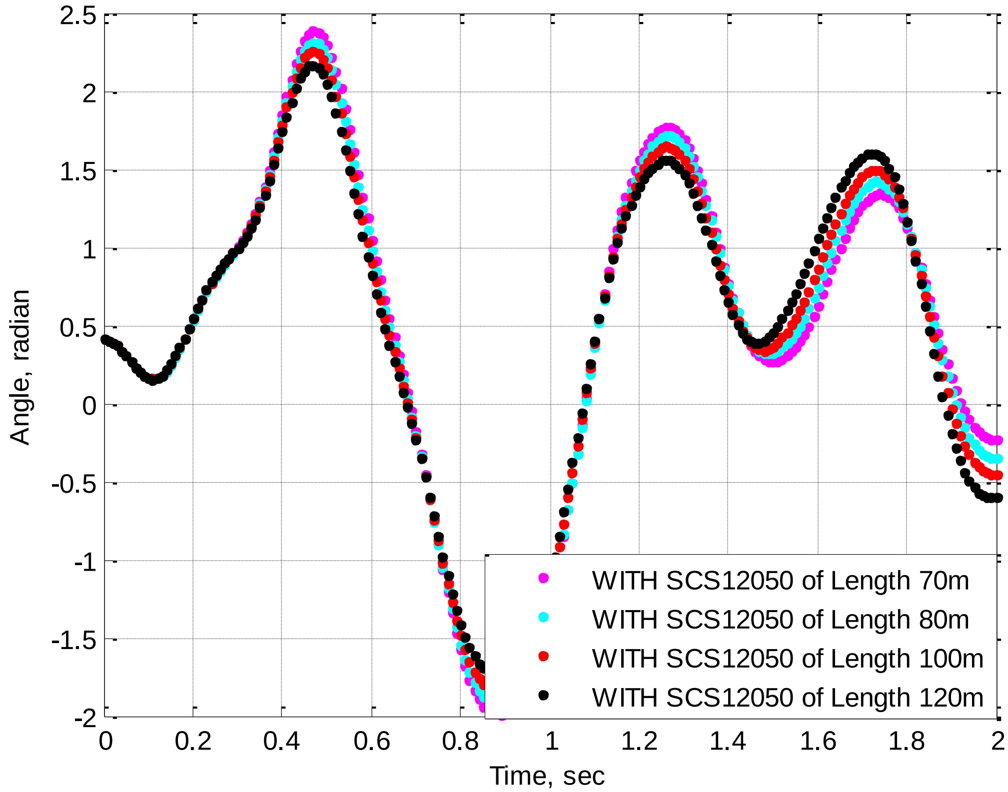

Figure 6: Swing curve of generator at Afam For SCS12050 of different Lengths (CCT = 850-ms)

4.4 Case 4: With SF12100 Coated Conductor

Applying a 3-phase fault on bus-6 leads to loss of synchronism to the generator at Afam generating station at a CCT of 850-ms without R-SFCL, but with R-SFCL with SF12100 coated conductor of different lengths, the generator was able to maintain synchronism at a CCT of 850-ms. Figure 7 shows the dynamic responses with R-SFCL with SF12100 coated conductor of different lengths.

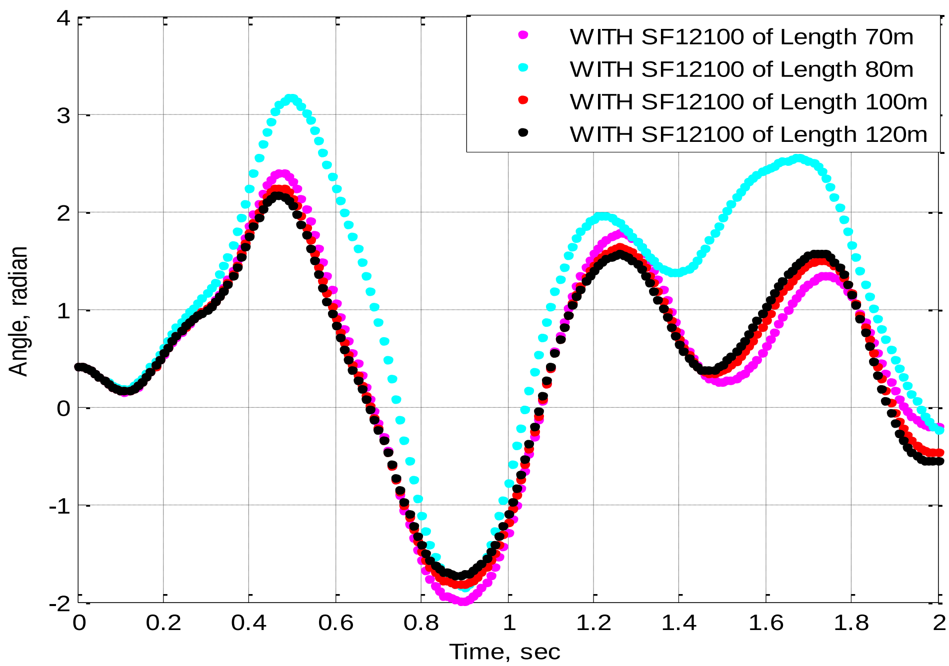

Figure 7: Swing curve of generator at Afam For SF12100 of different Lengths (CCT = 850-ms)

The result of CCT after a three-phase fault as seen from figure 5-7 are quite satisfactory with the applications of differents R-SFCLs. The results correlates with that of previous researcher [15].

V. CONCLUSIONS

This paper focuses on transient stability enhancement of the Nigeria 330-kV transmission network using Resistive-type Superconductor Fault Current Limiters of Coated Conductors of different lengths. The result shows that the generator at Afam generating station was the most severely disturbed generator when a 3-phase fault occurs on Aiyede bus (bus-6). The generator loss synchronism at a CCT of 850-ms, but with incorporation of a Resistive-type SFCL of different lengths, the system was able to maintain stability at a CCT of 850-ms. Thus, there is an improvement in the generator rotor angle of the generator at Afam power station. This research will be useful for future planning of the Nigeria 330-kV transmission grid. Also, further research should be done on appropriate sizing of the resistance value and location of the R-SFCL within the Nigeria 330-kV power station network with the sole aim of improving transient stability of the system.

REFERENCES

[1] Yagami M. and Tamura J., "Enhancement of Transient Stability using Fault Current Limiter and Thyristor controlled braking resistor", *In Proceeding of IEEE Power Tech*, 238-243, 2007.

[2] Hooshyar, H., Heydari, H., Savaghebi, M., and Sharifi, R., "Resistor-type Superconducting Fault Current Limiter: Optimum shunt Resistance determination to enhance Power System Transient Stability", *IEEJ Transactions on Power and Energy*, Aalborg University, 129, 299-308, 2009.

[3] Rob, S., "Development of Electricity Infrastructures in Sub-Saharan Africa", *International Conference on Global Trends in the Development of Power Transmission and Distribution Systems including Smart Grid*, 38-57, 2016.

[4] Feredouni, A.R., Vahidi, B., Mehr, T.H. and Doiran, M.G., "Enhancement of Power System Transient Stability and power quality using a Novel Solid-State Fault Current Limiter", *Journal of Electrical Engineering and Technology*, 6, 474-483, 2011.

[5] Zhang, X., Ruiz, H.S., Zhong, Z. and Coombs, T.A. (2016). "Implementation of Resistive-type SFCLs in Electrical grids: Performance analysis and measuring of optimal locations", http://arxiv.org/abs/1508.01162 accessed 29/04/2018.

[6] Chen, L., Chen, H., Yang, J., Yu, Y., Zhen, K., Liu, Y. and Ren, L., "Coordinated control of SFCL and Superconducting Magnetic Energy Storage for transient performance Enhancement of Grid-Connected Photovoltaic Generation System", *Journal of Energies*, 10, 1-23, 2017.

[7] Makinde, K., Enemuoh, F.O., Lawal, O.K., Umar, I., Abubakar, B. and Mahmood, M.K., "Performance analysis of surge current protection using Superconductors", *European Scientific Journal*, 10, 183-192, 2014.

[8] Rao, A.N. and Krishna, P.R., "The Fault level reduction in distribution system using an Active type SFCL", *International Journal of Engineering and Computer Science*, 5, 17392-17396, 2016.

[9] Mohamed, M.A. and Emad, A.M., "Enhancement of Multi-Machine Power System Transient Stability using Superconducting Fault Current Limiters with YBCO and Bi-2212", *International Journal on Power Engineering and Energy*, 5, 418-423, 2014.

[10] Byung, C.S. and Jung-wook, P., "A Study on Optimization of Resistive SFCL for Multi-Machine Power System using Eigen value Analysis" *Journal of International Council on Electrical Engineering*, 4, 167-172, 2014.

[11] Didier, G., Bonnard, C.H., Lubin, T. and Leveque, J., "Comparison between Inductive and Resistive SFCL in terms of current limitation and Power System Transient Stability", *Electric Power Systems Research, Elsevier*, 125, 1-16, 2015.

[12] Saumen, D., Alok, K.S., Pradip, K.S. and Ankur, G., "A Fault Current Limiter Circuit to improve Transient Stability in Power System", *International Journal of power Electronics and Drives System*, 7, 769-780, 2016.

[13] Biswas, A., Khan, M.E. and Sarker, U., "Transient Stability Improvement of a Conventional Power System by Superconducting Fault Current Limiter", *Global Journal of Researches in Engineering*, 13, 1-6, 2013.
[14] Dutta, S., "Modelling and analysis of Resistive-type Superconductor fault current limiter", *National Institute of technology Rourkela, Odisha, India, MSc. Thesis*; 1-42, 2004.
[15] Sabur, M. and Saad, B., "Comparative study of Resistive and Inductive Superconducting Fault Current Limiters (SFCL) for power system transient stability improvement", Journal of Superconductivity and Novel Magnetism, 26, 1-7, 2013.