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IMPROVING POWER TRANSMISSION SYSTEM TRANSIENT STABILITY USING PARTICLE SWARM OPTIMIZATION TECHNIQUE

[1]Nduka Samuel E., [2]Ilo F.U.
[1,2] Department of Electrical and Electronic Engineering, Enugu State University of Science and Technology, Enugu State, Nigeria

Corresponding Author Email: pneumahandco@gmail.com
Corresponding Author's Tel: +234 703 333 7641

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Abstract

This paper presents a study on improving power transmission system transient stability using the particle swarm optimization (PSO) technique. The research utilized two power systems, namely the IEEE 330KV standard 6-bus power system and the New Haven 330/132KV transmission network, as test beds. The study's objectives were achieved through five major steps. To start with, power system transient stability was characterized under normal operating conditions and transient disturbances for both power systems using load flow analysis in the Simulink modeSl. The second step involved modelling the Superconducting Solid-State Fault Current Limiter (SSSFCL) in Simulink, which helps enhance transient stability by limiting fault current magnitude during large-scale disturbances. In the third step, the PSO technique was employed to optimize the SSSFCL's parameters, ensuring optimal fault current limitation. The fourth step integrated the PSO-SSSFCL into the Simulink model of both power systems under fault conditions, and load flow analysis was conducted again. The results indicated that the PSO-SSSFCL effectively improves the transient stability of power transmission systems and is recommended for installation in sections with high fault current levels

Keywords: Power; Particle Swarm Optimization; Transient; Stability; Powergui; Simpower

1. INTRODUCTION

The electrical power system is made up of three major subdivisions which are the generation, transmission and distribution sectors. Power systems in some countries like Nigeria are very complicated and have a very high susceptibility to faults and the unavoidable occurrence of these faults have to a major extent contributed to power transmission system instability that we are facing today. In the past, various methods have been used to improve the stability of power system such as the use of protective equipment like instrument transformers, relays, fuses, circuit breakers, isolators and dc batteries, but these methods have not been able to improve the stability of the power transmission system much as needed. Hence, the need for more works in this regard to raise the improvement percentage to a higher level. According to (Hadi, 2006),power system stability is the ability of the power system to return to its normal operating conditions after a disturbance or perturbation. Power system stability is classified into two major types which are the steady state stability and transient stability. Steady state stability (also referred to as small disturbance voltage stability) is the ability of the power system to return to its normal operating conditions after a small disturbance or perturbation such as switching ON/OFF loads whereas transient stability (also referred to as large disturbance voltage stability) is the ability of the power system to return to its normal operating conditions after a large disturbance or perturbation. But this dissertation will focus on improving the transient stability of power systems.

In the event of fault in a power system, the current in the transmission lines goes high enough (a considerable percentage of the steady state current) thereby sending signals to the relays which in turn sends signals to the breakers to disconnect the faulty part of the system. These high fault currents may be caused by lightening, heavy winds, trees falling across lines, vehicles colliding with poles or towers, birds shorting lines, aircraft colliding with lines, vandalism, small animals entering switch gears etc. This paper will show how the particle swarm optimization techniques (PSOT) can be used to limit the magnitude of fault currents in the system during large disturbances. A fault current limiter (FCL), whether it employs a super conductor or not, is basically a variable impedance that is installed in series with a circuit breaker (Anderson, 2007). It resists the high fault current flowing in the network when a fault occurs. The parameters and location of the FCL will be optimized using the particle swarm optimization algorithm for optimal limiting of the fault current. By minimizing the magnitude of fault currents in a power system, the system will maintain a better stability during large disturbances.

2. LITERATURE REVIEW

Rautray et al., (2012) researched on the enhancement of power system transient stability using Thyristor Controlled Series Compensator (TCSC) controller and Particle Swarm Optimization. In the study, MATLAB was used to develop the model of the Single Mahine Infinite Bus (SMIB) power system with TCSC controller. The TCSC is formulated as an optimization problem then particle swarm optimization was used for retrieving the optimal control parameters. The result presents that the proposed controller is effective for damping small disturbance condition in the power system. Inkollu and Kota (2016) presented the optimal setting of Flexible AC Transmission System (FACTS) devices for improving voltage stability using an adaptive hybrid particle swarm algorithm and Gravitational Search Algorithm (GSA). In the study, the power loss system and voltage collapse rating are being determined using the FACTS devices. Secondly, the power flow in the transmission system is analyzed using Newton Raphson load flow study. Then, certain operating and physical constraints are satisfied while enhancing the voltage stability. Furthermore, Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) are used for evaluating the performance of the hybrid algorithms. The result of the study presented that the technique attained UPFC computational time of 23seconds while IPFC achieved a computational time of 18seconds. Mohammed (2018) presented a work on enhancement of power system transient stability by tuning of Static Synchronous Series Compensator(SSSC) and Power System Stabilizer(PSS) using Particle Swarm Optimization technique. The work minimizes the objective function of the system by tuning the speed of deviation and time domain which deviates deliberately at an oscillating angle of the alternator rotor. The result of the system implementation noted that it improves the power system stability when parameters of two controllers are tuned individually with tuning design of PSS and SSSC oscillation damping which results to enhancement in the power transient stability.

Al-Bahrani (2020) researched on the application of particle swarm optimization for the improvement of transient stability based on optimal power flow. In the work, Particle swarm optimization is used for minimization of three objective functions which are the fuel cost of thermal generation units, voltage deviation at the load buses and active power losses for the enhancement of transient stability and keep all the generators performing at a synchronous state through the system. The result of the study presented that the technique presented a voltage deviation of 0.0099pu and active losses of 3.33991MW. Singhal et al., (2014) presented a study on the use of particle swarm optimization for the enhancement of transient stability of a multi-machine system based on Unified Power Flow Controller (UPFC). The study modified the voltage stability by improving the power injection model for series voltage source of the UPFC and replacing the UPFC by equivalent admittance. Then, the required amount of series voltage injected by the UPFC controller is computed so as to damp the inter area and local mode of oscillations in multi-machine system. The work concluded by recommending the integration of additional auxiliary signals to supplement signals for better transient stability enhancement.

2.1 Particle Swarm Optimization Technique

The particle swarm optimization (PSO) technique is a heuristic algorithm-based technique that involves the simulation of the social behaviour of birds or fish within a flock (Al-Bahrani, 2018; Eberhart and Kennedy, 1995). In his own view (Miyuan et al., 2007) defined the particle swarm optimization (PSO) as a swarm intelligence algorithm inspired by the social dynamics and an emergent behaviour that arises in specially organized colonies. The PSO exploits a population of individuals to probe promising regions of the search space. In PSO, the individuals are usually regarded as particles and are flown through hyper-dimensional search space. The social psychological tendency of the individuals to emulate the success of the other individuals determines the changes in position of the particles within the search space. The search behaviour of a particle is thus affected by that of the other particles within the swarm. PSO is therefore a kind of symbiotic cooperative algorithm (Soliman et al., 2008). The velocity (V_x , V_y) and position (x, y) are used to represent the characteristic of each individual or agent in a two dimensional space. Each individual achieves its most desirable movement towards its target by doing the following (Valle et al., 2008):

1. Tracking the optimum value of the objective function which it has attained so far (i.e. the P_{best})
2. Tracking the optimum value of the objective function which the other individuals have attained so far (i.e. the g_{best})

Therefore, each individual updates its position taking note of

i. Its current velocity
ii. Its current position
iii. The spacing between the current position with g_{best} and p_{best}.

The flowchart in figure 1 explains the steps involved in a particle swarm optimization algorithm. The new position of an individual i in iteration k+1 (S_j^{k+1}) can be evaluated from its current (iteration k) position (S_j^k); provided that its velocity at iteration (k+1)(V_j^{k+1}) is known. The formula for determining (V_j^{k+1}) is given by:

$$V_j^{k+1} = WV_j^k + C_1\, \text{rand}_1\, (p_{besti} - S_i^k) + C_2\, \text{rand}_2\, (g_{best} - S_i^k) \qquad (1)$$

Where,

The weighting factor or diversification coefficient (W) is given by:

$$W = W_{max} - \left(\frac{W_{max} - W_{min}}{N_{it}max}\right) \times N_{it} \qquad (2)$$

Where W_{max}= maximum value of weighting factor ≅ 0.9
W_{min} = minimum value of weighting factor ≅ 0.4
N_{it} = no of iterations
$N_{it}max$ = maximum number of iterations.
W = weighting factor
C1, C2 = weighting coefficients ……….. 2.0
rand1 and rand2 = random numbers between 0 and 1

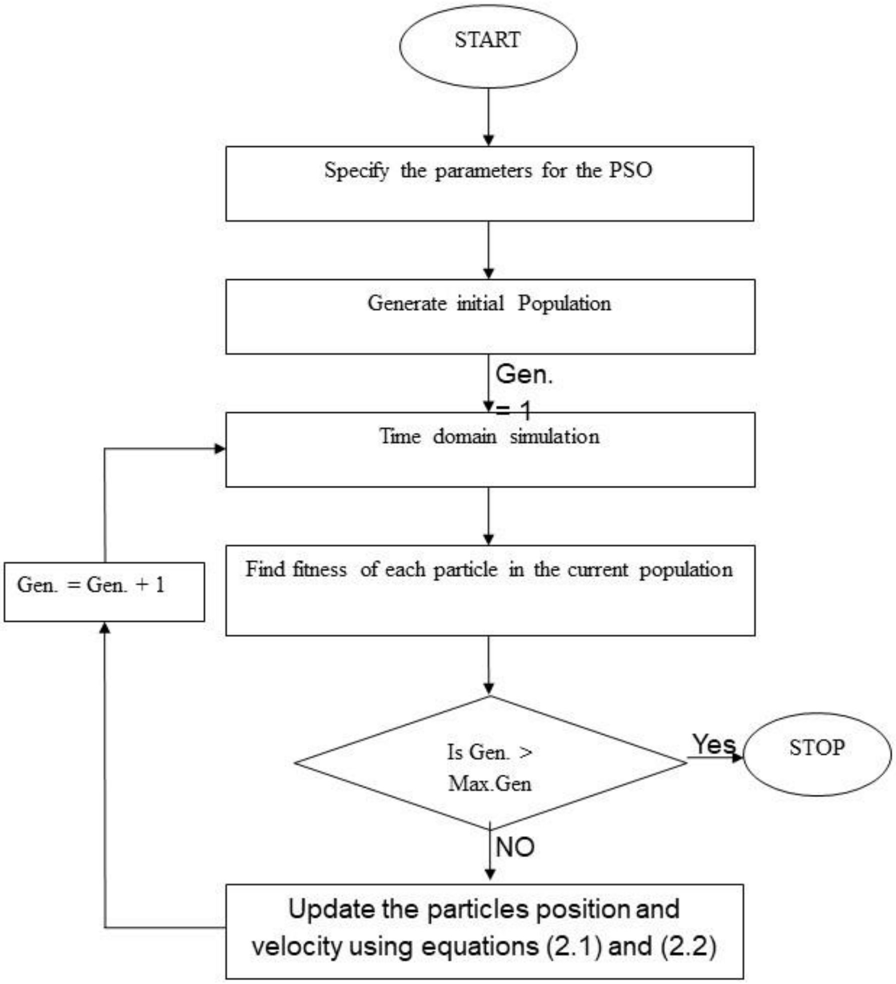

Figure1 - Flow Chart for Particle Swarm Algorithm

3. DESIGN METHOD

The major concern of this paper is to show how the transient stability of a power system can be improved upon by using the particle swarm optimized super-conducting solid state fault current limiter (SSSFCL) to limit the magnitude of fault current during large scale disturbances in the power system. First of all, the effects of faults on power system transient stability were investigated using the IEEE 330KV standard 6-bus power system and New Haven 330/132KV transmission network as a case study. The IEEE 6 bus test system data was obtained from www.ieee.org/publications_standards/index/html. It consists of 3 generators, 6 buses, 3 loads and 11transmission lines. The generators are rated at 250MVA, 187.5MVA and 222.5MVA respectively. The IEEE 6-bus power system and New Haven transmission network was modelled using Simulink and their test data (gotten from New Haven Transmission Station Data Base) was entered into their respective Simulink models. The load flow of both power systems was performed using the load flow and machine initialization tool from the power graphic user interface (Powergui) of simpower-systems in order to determine the degree of transient stability in the two power systems. The super conducting solid state fault current limiter (SSSFCL) and its control circuit was modelled using Simulink for limiting of the fault current through the unstable power systems. The parameters of the SSSFCL were optimized using the particle swarm optimization technique so as to achieve better limiting of the fault current during fault conditions. The particle swarm optimized super conducting solid state fault current limiter (PSO-SSSFCL) was integrated into the IEEE 330KV standard 6-bus power system and New Haven 330/132KV transmission network and the load flow was performed. The results of the load flow of both power systems obtained without PSO-SSSFCL installed and with PSO-SSSFCL installed were used to generate profiles of the various system parameters at the different conditions for assessing the degree of improvement in transient stability of the system.

4. MODEL FOR A SUPPER CONDUCTING SOLID STATE FAULT CURRENT LIMITER (SSSFCL) AND ITS CONTROL CIRCUIT

The single line diagram of the IEEE 330KV standard 6-bus power system is shown in figure 2.

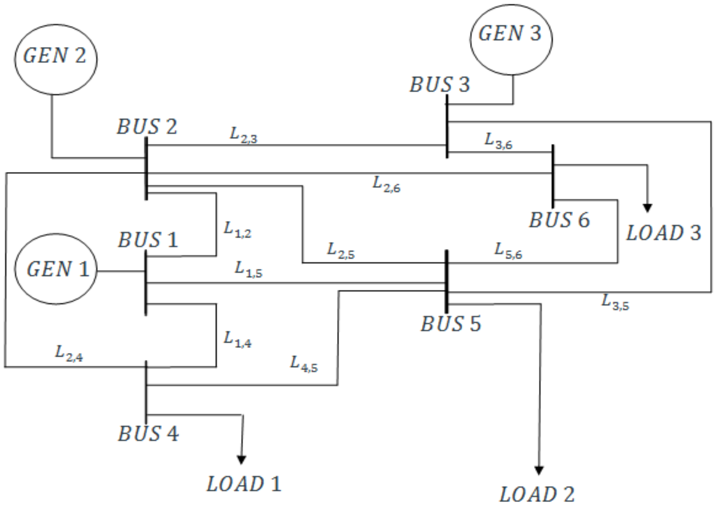

Figure 2: Single Line Diagram of the IEEE 330KV 6-Bus Power System

Consider any two buses say (i and k) with generators G_i and G_k extracted from the IEEE 330KV standard 6 bus power system of figure 3:

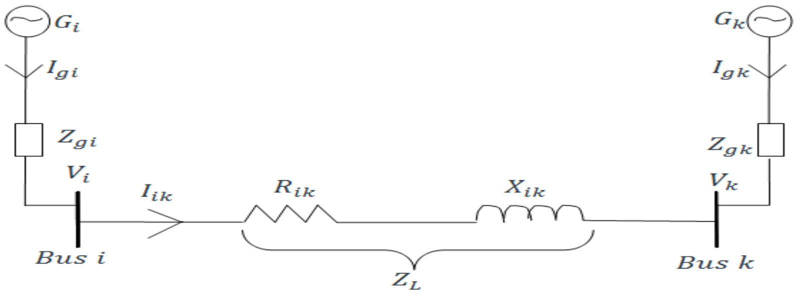

Figure 3: Transmission Line Model Extracted from the IEEE 330KV Standard 6-Bus Power System

Let Z_{gi} = impedance of generator i

Z_{gk} = impedance of generator k

Z_L = impedance of the transmission line

I_{ik} = current flowing in the network

V_i= magnitude of the voltage at bus i

V_k = magnitude of the voltage at bus k

Then under steady state conditions (ie when the system is healthy without disturbances or faults), the current flowing in the network will be given by

$$I_{ik} = \frac{V_i - V_k}{Z_{gi} + Z_L + Z_{gk}} = \frac{V_i - V_k}{Z_{eq}} \tag{3}$$

Where,

$$Z_{eq} = \text{the total impedance of the network} = Z_{gi} + Z_L + Z_{gk} \tag{4}$$

$$|Z_{gi}| = \sqrt{R_{gi}^2 + X_{gi}^2} \tag{5}$$

$$|Z_L| = \sqrt{R_L^2 + X_L^2} \tag{6}$$

$$|Z_{gk}| = \sqrt{R_{gk}^2 + X_{gk}^2} \tag{7}$$

In this case the network current (I_{ik}), bus voltages V_i and V_k assume their steady state values when the load flow is performed. However, under fault conditions (may be say a three-phase fault with fault impedance Z_f occurs at bus k then the modified diagram of figure 4:

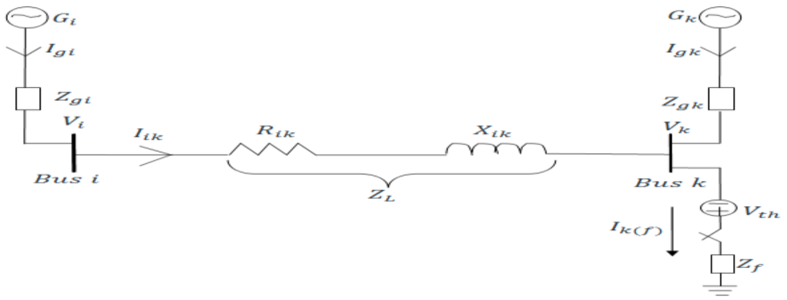

Figure 4: The Power System under Fault Conditions

Then the total impedance of the network during the fault will be given by

$$Z_{eq} = (Z_{gi} + Z_L)||Z_{gk} = \frac{(Z_{gi}+Z_L)\times Z_{gk}}{Z_{gi}+ Z_L+ Z_{gk}} \qquad (8)$$

According to Thevenin's theorem, the changes in the network voltage caused by the added branch is equivalent to those added voltage with all other branches short circuited as shown in figure 5:

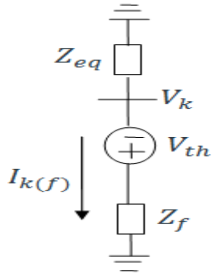

Figure 5: Thevenin's Equivalent Network

From figure5, the fault current at bus k will be given by

$$I_{k(f)} = \frac{V_{th}}{Z_{eq}+ Z_f} \qquad (9)$$

But since$V_{th} = V_k$, then

$$I_{k(f)} = \frac{V_k}{Z_{eq}+ Z_f} \qquad (10)$$

The current divisions between the two generators $G_i$and G_k during the fault is given by

$$I_{gi} = \left(\frac{Z_{gk}}{Z_{gi} + Z_L + Z_{gk}}\right) \times I_{k(f)} = \frac{V_k Z_{gk}}{Z_{gk}(Z_{gi}+Z_L)+Z_f(Z_{gi}+Z_L+Z_{gk})} \qquad (11)$$

$$I_{gk} = \left(\frac{Z_{gi} + Z_L}{Z_{gi} + Z_L +Z_{gk}}\right) \times I_{k(f)} = \frac{V_k(Z_{gi}+Z_L)}{Z_{gk}(Z_{gi}+Z_L)+Z_f(Z_{gi}+Z_L+Z_{gk})} \qquad (12)$$

The changes in the bus voltages during the fault is given by

$$\Delta V_i = 0 - Z_{gi}I_{gi} = -\frac{V_k Z_{gi} Z_{gk}}{Z_{gk}(Z_{gi}+Z_L)+Z_{f(Z_{gi}+Z_L+Z_{gk})}} \qquad (13)$$

And the change in bus k is given by

$$\Delta V_k = 0 - Z_{gk}I_{gk} = -\frac{V_k Z_{gk}(Z_{gi}+Z_L)}{Z_{gk}(Z_{gi}+Z_L)+Z_f(Z_{gi}+Z_L+Z_{gk})} \qquad (14)$$

The bus voltages during the fault will be obtained by superposition of the pre-fault bus voltages and the changes in the bus voltages caused by the equivalent emf connected to the faulted bus.

$$Ie\ V_{i(f)} = V_i + \Delta V_i = V_i - \frac{V_k Z_{gi} Z_{gk}}{Z_{gk}(Z_{gi}+Z_L)+Z_f(Z_{gi}+Z_L+Z_{gk})} \qquad (15)$$

And

$$V_{k(f)} = V_k + \Delta V_k = V_k - \frac{V_k Z_{gk}(Z_{gi}+Z_L)}{Z_{gk}(Z_{gi}+Z_L)+Z_f(Z_{gi}+Z_L+Zgk)} \qquad (16)$$

The fault current now flowing between buses i and k is then given as

$$I_{ik(f)} = \frac{(V_{i(f)} - V_{k(f)})}{Z_L} = \frac{V_i}{Z_L} - V_k\left(\frac{1}{Z_L} - \frac{Z_{gk}Z_L}{Z_{gk}(Z_{gi}+Z_L)+Z_f(Z_{gi}+Z_L+Z_{gk})}\right) \qquad (17)$$

Equation 17 indicates that the introduction of the fault current ($I_{k(f)}$) will make the network current (I_N) to rise above the steady state values thereby resulting in voltage drops in the buses during the fault.

Consider that the SSSFCL was installed at the receiving end of the transmission line from bus i to bus k as shown in figure 6. Since the shunt path of the SSSFCL has very high impedance, the current in the network will flow through the bridge path during the positive or negative half cycle of the electrical frequency under normal operating conditions.

Hence,

$$I_N = I_{fcl} = I_{Zdc} \tag{18}$$

Where $Zdc = \sqrt{R_{dc}^2 + X_{dc}^2}$

$$I.e\ I_{fcl} = I_{bridge} = I_{Zdc}$$

Under fault conditions

$$I_{bridge} = I_{th} \tag{19}$$

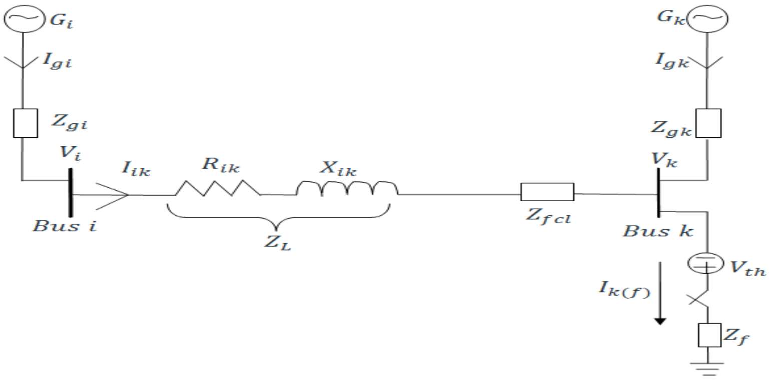

Figure 6: Power System with SSSFCL Installed at the Receiving End of the Transmission Line

Where I_{th} = the threshold value or the maximum permissible current through the bridge path

Then $V_{ge} = I_{bridge} = 0$ (20)

As the bridge path disconnects from the system, the equivalent impedance during the SSSFCL operation will be given by

$$Z_{eq} = (Z_{gi} + Z_L + Z_{fcl})||Z_{gk} = \frac{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})}{Z_{gi}+Z_L+Z_{fcl}+Z_{gk}} \tag{21}$$

And from Thevenin's theorem, the fault current at bus k will now be given by

$$I_{k(f)} = \frac{V_{th}}{Z_{eq}+Z_f} = \frac{V_k}{\frac{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})}{Z_{gi}+Z_L+Z_{fcl}+Z_{gk}}+Z_f} \tag{22}$$

The generator currents will be given by

$$I_{gi} = \frac{Z_{gk}}{Z_{gi}+Z_L+Z_{fcl}+Z_{gk}} \times I_{k(f)} = \frac{V_k Z_{gk}}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})} \tag{23}$$

$$I_{gk} = \left(\frac{Z_{gi}+Z_L+Z_{fcl}}{Z_{gi}+Z_L+Z_{fcl}+Z_{gk}}\right) \times I_{k(f)} = \frac{V_k(Z_{gi}+Z_L+Z_{gk})}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+ Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})} \tag{24}$$

The change in the bus voltages will be given by

$$\Delta V_i = 0 - Z_{gi}I_{gi} = -\frac{V_k Z_{gi} Z_{gk}}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})} \tag{25}$$

$$\Delta V_k = 0 - Z_{gk}I_{gk} = -\frac{V_k Z_{gk}(Z_{gi}+Z_L+Z_{fcl})}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})} \qquad (26)$$

The bus voltages during the fault will then be given by

$$V_{i(f)} = V_i + \Delta V_i = V_i - \frac{V_k Z_{gi} Z_{gk}}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})} \qquad (27)$$

$$V_{k(f)} = V_k + \Delta V_k = V_k - \frac{V_k Z_{gk}(Z_{gi}+Z_L+Z_{fcl})}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})} \qquad (28)$$

The limited current now flowing between bus i and k will be given by

$$I_{ik(limited)} \frac{(V_{i(f)}-V_{k(f)})}{Z_L+Z_{fcl}} = \frac{V_i}{Z_L+Z_{fcl}} - V_k\left(\frac{1}{Z_L+Z_{fcl}} - \frac{Z_{gk}(Z_L+Z_{fcl})}{Z_{gk}(Z_{gi}+Z_L+Z_{fcl})+Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})}\right) \qquad (29)$$

Equation 29 indicates that by controlling the magnitude of Z_{fcl}, the fault current through the transmission lines will be minimized.

5. TO OPTIMIZE THE PARAMETERS OF THE SSSFCL MODEL USING THE PARTICLE SWARM OPTIMIZATION

In equation 29, only Z_{fcl} is unknown as all other variables are already specified. This gives rise to the need to optimize Z_{fcl} for better limiting of the fault current. Hence from equation 29,

Let

$$\frac{1}{Z_L+Z_{fcl}} = x_1 \qquad (30)$$

$$\frac{Z_{gi}+Z_L+Z_{fcl}}{Z_L+Z_{fcl}} = x_2 \qquad (31)$$

$$\frac{Z_f(Z_{gi}+Z_L+Z_{fcl}+Z_{gk})}{Z_{gk}(Z_L+Z_{fcl})} = x_3 \qquad (32)$$

Using equations 30, 31 and 32 in 33 gives

$$I_{ik(limited)} = (V_i - V_k)x_1 + V_k x_2 - V_k x_3 \qquad (33)$$

For the IEEE 330KV standard 6 bus power system, the objective function and the constraints was formulated using the results from table 4.5 and 4.6 and using line 5-6 for objective function and lines 5-6, 3-6 and 1-2 for the constraints. The optimization equation therefore become:

$$Minimize\ I_{ik(limited)} = 35265.22x_1 + 270993.23x_2 - 270993.23x_3 \qquad (34)$$

Subject to the constraints: $35265.22x_1 + 270993.23x_2 - 270993.23x_3 \leq -28.06$

$$59006.43x_1 + 270993.23x_2 - 270993.23\,x_3 \leq -126.39$$

$$329999.66x_2 - 329999.66\,x_3 \leq -182.27$$

For New Haven 330/132KV transmission network, the objective function and the constraints was formulated using the results from table 1 and 2, and using New Haven – Ugwuaji 330KV line for the objective function and Ugwuaji – Markudi 330KV line, New Haven – Nkalagu 132KV line and Nkalagu - Abakaliki 132 KV line for the constraints. The New Haven transmission optimization problem model therefore became:

$$Minimize\ I_{ik(limited)} = 859.83x_1 + 313502.98x_2 - 313502.98x_3 \qquad (35)$$

Subject to the constraints: $46930.6x_1 + 266528.29x_2 - 266528.29x_3 \leq 144.09$

$$54.21x_1 + 119045.76x_2 - 119045.76x_3 \leq 64.62$$

$$74.86x_1 + 118970.90x_2 - 118970.90x_3 \leq 0.1$$

Table 1: Summary of the IEEE 6-Bus Load Flow Results under normal Operating Conditions

QUANTITY	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6
VOLTAGE (V)	329999.66	329999.66	329999.66	317314.65	317431.36	315308.28
CURRENT (A)	156.03	338.30	263.15	339.53	334.48	362.54
ACTIVE POWER (MW)	123.5756	267.9333	208.4146	258.5708	254.8187	274.3485
REACTIVE POWER(MVAR)	92.6817	200.9499	156.3110	193.9281	191.1140	205.7614
BUS ANGLE (Deg)	66.87°	66.87°	66.87°	65.03°	64.38°	65.12°

Table 2: Summary of the IEEE 6-Bus Load Flow Results under Transient Disturbance

QUANTITY	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6
VOLTAGE(V)	329999.66	329999.66	329999.66	315761.52	306258.45	270993.23
CURRENT (A)	235.57	921.23	1192.96	380.89	583.74	1880.92
ACTIVE POWER (MW)	186.5712	729.6134	944.8233	288.6490	429.0607	1223.3198
REACTIVE POWER (MVAR)	139.9284	547.2101	708.6174	216.4868	321.7955	917.4899
BUS ANGLE (Deg)	66.87°	66.87°	66.87°	64.69°	62.01°	52.45°

The MATLAB program for solving the optimization problem of equation 34 and 35 using the particle swarm optimization (PSO) algorithm. The parameters for the optimization are given below:

No of variables $(m) = 3$
No of particles $(n) = 2000$
Minimum initial weight $(W_{min}) = 0.4$
Maximum initial weight $(W_{max}) = 0.9$
Lower bound of variables $(LB) = 0$
Upper bound of variables $(UB) = 2$
Acceleration factor$(C_1) = 2$
Acceleration factor $(C_2) = 2$
Maximum number of iterations$(iter_{max}) = 1000$

6. SYSTEM INTEGRATION

The Particle Swarm Optimized Super Conducting Solid State Fault Current Limiter (PSO-SSSFCL) was integrated into the Simulink model of both power systems under transient disturbance. For the IEEE 330KV standard 6-bus power system, the PSO-SSSFCL was installed in bus 6, line 5-6 and line 1-2 and for the New Haven 330/132KV transmission network, the PSO-SSSFCL was installed in Ugwuaji – Markurdi 330KV line and New Haven 132KV bus 1 for optimal limiting of fault current through the system. This is shown in fig 3.17 and 3.18 respectively. The PSO-SSSFCL blocks in the Simulink model of the IEEE 330KV standard 6 bus power system and New Haven 330/132KV transmission network is a subsystem of the SSSFCL Simulink model in research objective 2. They are labelled according to the phases to which they are connected (Phase A, Phase B and Phase C) respectively. The PSO-SSSFCL subsystem also contains the control circuit of the SSSFCL. The load flow of both power systems is performed with the PSO-SSSFCL attached thereby ensuring that the SSSFCL is used to modify the load flow parameters of the system. The results as analysed in objective four indicated that the integration of the PSO-SSSFCL improved the bus voltage profiles by minimizing the voltage deviation during the fault and limiting the impact of the fault current in the system. Fig 3.19 shows the flowchart of power flow with SSSFCL. The flowchart is the same with that for objective one except that the parameters of the SSSFCL were read as input and used to modify the Jacobian matrix of both power systems.

7. RESULT AND DISCUSSION

The objective function and the constraints were based on equation 3.27. For IEEE 330KV standard 6-bus power system, the objective function was formulated using data from line 5-6 while the constraints were formulated using data from line 5-6 for constraint 1, line 3-6 for constraint 2 and line 1-2 for constraint 3. The constraints were also formulated based on the difference in current between the buses under normal operating conditions. For the New Haven 330/132KV transmission network, the objective function was formulated using New Haven – Ugwuaji 330KV line data while the constraints were formulated using Ugwuaji – Makurdi 330KV line data for constraint 1, New Haven – Nkalagu 132KV line data for constraint 2, and Nkalagu – Abakaliki 132KV line data for constraint 3.

The single phase PSO-SSSFCL was installed at bus 6, line 5-6 and line 1-2 of the IEEE 6 bus power system with fault and the New Haven 330/132KV transmission network with fault and the load flow was performed. The operation of the PSO-SSSFCL showed that when the system voltage is below the reference voltage due to fault, the gate signal of the IGBT becomes low and control is transferred to the shunt path but when the fault is cleared, the IGBT gate signal becomes high again and the bridge path regains control. The screen shot of the results are shown in figure7 and8 and summarized in table 3,4 and 5 respectively.

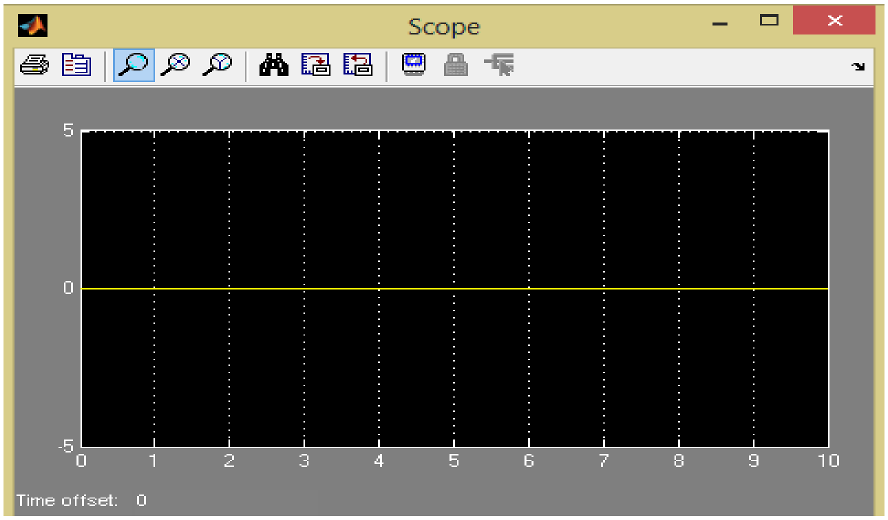

Figure 7: Gate Signal of the IGBT when the System Voltage is below the Reference Voltage

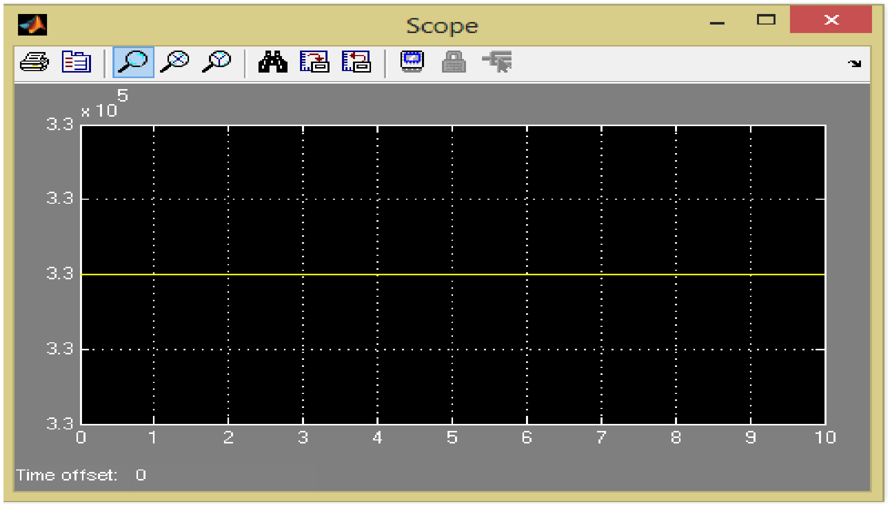

Figure 8: Gate Signal of the IGBT during normal Operating Conditions

Table 3: Summary of the IEEE 6-Bus Load Flow Results with Fault and PSO-SSSFCL Installed

QUANTITY	**BUS 1**	**BUS 2**	**BUS 3**	**BUS 4**	**BUS 5**	**BUS 6**
VOLTAGE (V)	329999.66	329999.66	329999.66	321548.67	339212.17	320272.55
CURRENT(A)	0.51	462.55	420.66	281.08	30.71	362.54
ACTIVE POWER (MW)	0.4039	366.3392	333.1624	216.9142	25.0013	278.6679
REACTIVE POWER(MVAR)	0.3029	274.7544	249.8718	162.6857	18.7510	209.0009
BUS ANGLE (Deg)	66.87°	66.87°	66.87°	64.61°	65.19°	62.66°

Table 4: Summary of New Haven 330KV Load Flow Results with Fault and PSO-SSSFCL Installed

PARAMETER	**330KV BUS 1**	**330KV BUS 2**	**330KV BUS 3**	**330KV BUS 4**	**330KV BUS 5**
VOLTAGE (V)	329999.66	323858.76	323515.10	329999.66	324385.02
CURRENT (A)	881.39	867.99	148.64	614.25	5.24
ACTIVE POWER (MW)	698.0602	674.6548	115.4095	486.4855	4.0794
REACTIVE POWER (MVAR)	523.5452	505.9911	86.5571	364.8641	3.0596
BUS ANGLE (Deg)	66.87°	66.63°	66.62°	66.87°	66.64°

Table 5: Summary of New Haven 132KV Load Flow Results with Fault and PSO-SSSFCL Installed

QUANTITY	**132KV BUS 1**	**132KV BUS 2**	**132KV BUS 3**	**132KV BUS 4**	**132KV BUS 5**
VOLTAGE (V)	127268.23	127604.06	127642.55	127643.10	127548.65
CURRENT (A)	509.54	494.92	4.08	4.21	494.75
ACTIVE POWER (MW)	155.6358	151.5691	1.2499	1.2897	151.4513
REACTIVE POWER (MVAR)	116.7269	113.6768	0.9374	0.9673	113.5885
BUS ANGLE (Deg)	50.18°	48.95°	48.94°	48.95°	48.95°

As can be seen from table 3, the integration of the PSO-SSFCL in the IEEE 330KV standard 6 bus power system during the fault improved the voltage profile at bus 4, 5 and 6 by 3.26%. The current at bus 1 was reduced to 0.51A ($99.78\%\ reduction$) that at bus 2 was reduced to 462.55A ($49.79\%\ reduction$), current at bus 3 was reduced to 420.66A ($64.74\%\ reduction$), while that at bus 4 was reduced to 281.08A ($26.20\%\ reduction$). The current at bus 5 was reduced to 30.71A ($94.74\%\ reduction$) while that at bus 6 was reduced to 362.54A ($80.73\%\ reduction$). The New Haven 330/132KV load flow results with PSO-SSSFCL installed showed that the voltage profile of New Haven 330KV transmission network was improved by 4.98% while the current rise was minimized by 80.23%. The voltage profile of New Haven 132KV transmission network was improved by 7.12% while the current rise was minimized by 34.26% during the fault.

8. CONCLUSION AND RECOMMENDATION

This paper described exhaustively how power system transient stability can be improved upon by using the particle swarm optimized super conducting solid state fault current limiter (PSO-SSSFCL) to limit the magnitude of fault current in the power system during large scale disturbances. The test systems used for the analysis was the IEEE 330KV standard 6 bus power system and the New Haven 330/132KV transmission network which was modelled in Simulink and the load flow analysis were carried out under normal operating conditions and during fault conditions. The SSSFCL was modelled in Simulink and the parameters were optimized using the particle swarm optimization algorithm implemented in MATLAB. This optimized SSSFCL was integrated into the IEEE 330KV standard 6 bus power system and New Haven 330/132KV transmission network with fault and the load flow was performed. The results were used to generate and compare the voltage profiles and current waveforms of the two power systems both without PSO-SSSFCL installed and with PSO-SSSFCL installed respectively, and it was discovered that the integration of the PSO-SSSFCL minimized the current flow between the buses by 58.04% for IEEE 330KV standard 6-bus power system and 56.34% for New Haven 330/132KV transmission network. The results also proved that the transient stability of the IEEE 330KV standard 6-bus power system improved by 4.48% while that for New Haven transmission network improved by 3.42% during the fault. It can therefore be concluded that the PSO-SSSFCL is capable of improving power system transient stability.

8.1. RECOMMENDATIONS

Some of these issues should be addressed in future research works in this subject area:

1. The optimization of the SSSFCL in the power systems should be carried out using other heuristic algorithms like the tabu search (TS), simulated annealing (SA), ant colony (AC) etc
2. Complex power systems with numerous buses should be modelled using software like the power system analysis tool box (PSAT), PSCAD, LT-SPICE, NEPLAN etc
3. The super conducting solid state fault current limiters should be installed in those sections of the transmission network that is mostly affected by faults in order to limit the magnitude of the fault current during fault conditions. This will help in safe guarding electrical equipment during faults conditions, minimize damage and repair cost, improve the power system stability and power quality and also ensure safety of personnel

9. REFERENCES

Hadi S., (2006) “Stabiliy Analysis of Pi-kinks in a 0-pi Josephson Junction”, 2006; pp. 3-6.

Anderson J., (2007) “Integration of Control Software and Numerical Analysis for Electrical Machines and Drives Teaching Studio”. 2007; pp. 1-3

Rautray S., Choudhury S., Mishra S., & Rout P., (2012) “A Particle Swarm Optimization Based Approach For Power System Transient Stability Enhancement With TCSC”, 2nd International Conference on Communication, Computing & Security [ICCCS-2012]

Inkollu S., & Kota V., (2016) “Optimal setting of FACTS devices for voltage stability improvement using PSO adaptive GSA hybrid algorithm”, Engineering Science and Technology, an International Journal. http://dx.doi.org/10.1016/j.jestch.2016.01.011

Mohammed H., (2018) “Power System Transient Stability Enhancement by Tuning of SSSC and PSS Parameters Using PSO Technique”, Journal of University of Babylon, Engineering Sciences, Vol.(26), No.(5): 2018.

Al-Bahran L., (2020) “Transient Stability Improvement based on Optimal Power Flow using Particle Swarm Optimization”, ICEAT 2020 IOP Conf. Series: Materials Science and Engineering 870 (2020) 012118 IOP Publishing doi:10.1088/1757-899X/870/1/012118

Singghal P., Agarwal S., & Kumar N., (2014) “Transient Stability Enhancement of a Multi-Machine System using Particle Swarm Optimization based Unified Power Flow Controller”, Poonam Singhal et al Int. Journal of Engineering Research and Applications www.ijera.com ISSN : 2248-9622, Vol. 4, Issue 7(Version 3), July 2014, pp.121-133

Miyuan S., Juan W., Danni P., (2007) “Particle Swarm and Ant Colony Algorithm Hybridized for Multi-mode Resource-Constrained project scheduling problem with minimum time Lag”, IEEE conference Pp 5898-5902

Soliman H., Bayoumi E., & Hassan M., (2008) “PSO-Based Power System Stabilizer For Minimal Overshoot and Control Constraints”, Jour. of Elec. Eng.,Vol. 59, No. 3, pp. 153.

Valle D., Agamoorthy V., & Mohagheghi G., (2008) “Particle swarm optimization: Basic concepts, variants and application in power systems”, IEEE Transactions on Evolutionary Computation 12, pp. 171-195)

AL-bahrani L T 2018 ‘’Transient Stability Optimization based on increasing the Critical Clearing Time using Particle Swarm Optimization’’ International Journal of Engineering & Technology, 7, (4.19), pp. 874-879

Eberhart R., & Kennedy J., (1995) “A new optimizer using particle swarm theory”, In Proceedings of the Sixth International Symposium on Micro Machine and Human Science, Nagoya, Japan, 4–6 October 1995; pp. 39–43