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Performance Assessment of Thyristor Controlled Series Compensator (TCSC) in Sudanese National Grid

تقييم أداء معوض التوالي المتحكم به عن طريق الثايرستور في الشبكة القومية السودانية

A Thesis submitted in partial fulfillment for the requirement

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الآية

بسم الله الرحمن الرحيم

قال تعالي :

﴿ قَالُواْ سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ﴾

سورة البقرة (32)

DEDICATION

To Mom and Dad

To my family

To my teachers

To my colleagues

ACKNOWLEDGEMENT

First and foremost, I must acknowledge my limitless thanks to Allah, the Ever-Magnificent; the Ever-Thankful, for His helps and bless. I am totally sure that this work would have never become truth, without His guidance. I am grateful to some people, who worked hard with me from the beginning till the completion of this thesis particularly my supervisor **Dr. Mohammed Osman Hassan**, who has been always generous during all phases of the thesis. I would like to take this opportunity to say warm thanks to **Mr. Ahmed Mohammed Abdelgadir**, who have been so supportive along the way of doing my thesis. I also would like to express my whole hearted thanks to my family for their generous support they provided me throughout my entire life and particularly through the process of pursuing the master degree.

Abstract

In this thesis a method based on Particle Swarm Optimization (PSO) algorithm, which represents one type of modern optimization techniques is presented to determine the optimal parameters of Power System Stabilizers (PSSs) found in Sudanese National Grid, instead of classical control approaches. In addition TCSC is implemented in the National grid to increases the performance of the system by decreasing reactance of the transmission lines and hence increases the power flow in the lines as well as reduces the line losses. Optimal location for placing of TCSC is found by performance indices calculation to reduce overloading of each transmission line in normal case and contingency cases. TCSC improve system damping. The simulation carried out through MATLAB and POWER FACTORY software. Therefore as a result the TCSC enhance National Grid performance through decreasing transmission lines overloading under normal and contingency conditions. Also activation of power system stabilizers found in the National Grid and TCSC implementation had a significant role in enhancing damping in National grid.

مستخلص

في هذه الأطروحة تم تقديم طريقة تعتمد على خوارزمية تجسيم سرب الجسيمات (PSO) ، والتي تمثل نوعًا واحدًا من تقنية التحسين الحديثة لتحديد المتغيرات المثلى لمثبتات نظام القدرة (PSS) الموجودة في الشبكة القومية لكهرباء السودان، بدلاً من طرق التحكم التقليدية. بالاضافة لذلك تم تمثيل معوض التوالي المتحكم به عن طريق الثايرستور(TCSC) في الشبكة القومية لزيادة فعالية النظام عن طريق تقليل المفاعلات الحثية لخطوط النقل وبالتالي زيادة القدرة المنقولة عن طريق هذه الخطوط وتقليل الفقد فيها. الموقع الامثل لربط معوض التوالي المتحكم به عن طريق الثايرستور (TCSC) تم حسابه عن طريق معاملات الأداء لتقليل التحميل على خطوط النقل في الحالة الطبيعية وفي الحالات الطارئة. وأيضا تم ملاحظة زيادة تخميد النظام بعد اضافة معوض التوالي المتحكم به عن طريق الثايرستور (TCSC). المحاكاة تم عن طريق برنامجي الماتلاب وال DIGSILENT .وعليه كنتيجة وجد ان معوض التوالي المتحكم به عن طريق الثايرستور لعب دورا مهما في تحسين مستوى الاداء في الشبكة القومية وذلك عن طريق تقليل تحميل خطوط النقل في حالة التشغيل الطبيعية وكذلك في حالة فقدان الخطوط. وايضا تفعيل وضبط مثبتات نظام القدرة الموجودة في الشبكة القومية واضافة معوض التوالى المتحكم به عن طريق الثايرستور لعبا دورا مهما في تحسين مستوى التخميد في الشبكة القومية.

TABLE OF CONTENTS

CHAPTER FOUR
MODERN METHODS OF OPTIMIZATION

CHAPTER FIVE
SIMULATION AND RESULTS DISCUSSION

CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

FACTS	Flexible AC Transmission system
TCSC	Thyristor Controlled Series Compensator
PSS	Power System Stabilizer
PSO	particle swarm optimization
OPF	Optimal Power Flow
ISO	Independent System Operator
IL	Interruptible Load
GA	Genetic algorithm
POD	power oscillation damper
PIp	Active power performance index
CPI	Contingency capacity Performance index

CHAPTER ONE

INTRODUCTION

1.1 Overview

In present days, Power demand is increasing every year to meet this demand the expansion of power generation and transmission is necessary. But at the same time it is limited due to limited resources and environmental restrictions. Installation of new transmission lines with the large interconnected power system are limited to some of the factors like economic cost, environment related issues. As a consequence some transmission lines are heavily loaded. The proposed concept is power electronics based technology has been mainly used for solving various power system control problems. [1]

Continuous and fast improvement of power electronics technology has made FACTS (Flexible AC Transmission system) a promising concept for power system development in the coming decade. Among a variety of FACTS devices, Thyristor controlled series compensator (TCSC) is chosen and well designed to enhance the transient stability of the power system. [2]

TCSC increases the performance of system decreasing reactance of line and hence increases the power flow in the line but cost of FACTS device is high. An approach to determine the most suitable location for placing the TCSC in order to enhance the power flow in transmission line using contingencies analysis and ranking. So it is required to find optima location of FACTS device. Performance indices are defined and ranked to place TCSC in line which informs to locate TCSC in better position.

Over the last half-century, many power system researchers and engineers have worked on and contributed to the understanding and solution of the problem of power system oscillations. It is now well recognized that the main cause of power system oscillations is the poor damping of the so-called electromechanical oscillation modes of the power system. Poor damping could be brought out by the (1) large amount of long-distance power transmission, (2)weak interconnection of large power sub-networks, and or (3) negative damping due to the fast-acting high-gain AVRs. Most of the new generators connected to electric utility systems were equipped with continuously-acting voltage regulators. [3] Thus, the power system stabilizers are developed to aid in damping these oscillations via modulating the generator excitation.

1.2 Problem Statement

Recently some modifications have been carried out in Sudanese National grid to improve system performance but until now there are several problems not solved such as:

i. Over loading of transmission lines under normal operating conditions and under contingency conditions.
ii. Sudanese National grid contains four power system stabilizers (PSSs) but only two of them are working and the others are in off-line mode which lead to reduction in damping ratios as a result the dynamic stability of the system has affected.

1.3 Objectives

The objectives of this thesis are:

i. Reactivate all power system stabilizers (PSSs) found in Sudanese National grid.
ii. Tuning the PSSs parameters using modern optimization technique through using particle swarm optimization (PSO) technique.
iii. Solving the transmission lines over loading using Thyristor Controlled Series Compensator (TCSC) under normal condition and under contingency condition. Then performance indices are used to find the optimal location of TCSC.
iv. Comparing the damping ratios of the system with PSSs and TCSC and without them under normal operating condition.

1.4 Methodology

The first stage in this project; Sudanese National Grid was implemented in DIGSILENT (Power Factory) software environment then power flow was performed for the national grid.

On second stage all power system stabilizers (PSSs) found in the system were activated and then tuned using particle swarm optimization (PSO) technique through linking POWERFACTORY software with MATLAB.

On third stage performance indices were used to find optimal location of TCSC under normal condition and under contingency condition.

On the final stage TCSC parameters were calculated then the effect of TCSC modeling in the transmission lines over loading was considered also the effect of PSSs and TCSC on damping ratios under normal operating conditions was illustrated.

1.5 Thesis Outlines

This thesis including six chapters as follow: Chapter one is introduction including overview about the role of TCSC in improving power systems performance through decreasing line reactance and hence increasing power flow in transmission lines under normal and contingency conditions. In addition the overview presents the effect of PSS on power system damping. Also this chapter contains problem statement, objective and methodology; while chapter two is literature review. Chapter three gives information about TCSC and PSS modeling also introduces the performance indices which used to find TCSC optimal location. Chapter four includes an introduction of optimization methods and focus on PSO and how to use it to determine optimal parameters of PSS. Chapter five consists of study calculations and simulations results. And finally chapter six includes the conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

*2.*1 Introduction

Power system is facing new challenges and opportunities in the environment of the internet of things. Under the circumstance of Internet of things, the transmission congestion management of interruptible load is the important measure to improve system reliability and operating economy. Considering the condition of target selected under different circumstances.

2.2 Past Research on Transmission Lines Congestion Elimination

The rise of the Internet of things, make the power system has to face many new problems. As at the beginning the rise of the Internet, and the problems faced in today's power system also need to face more and more serious transmission congestion problem. With the opening up of the grid and cross-regional electrical energy trade increasing, the deepening of power market reform, it is necessary to carry out a wider range of optimal allocation of resources. The gradual opening of demand side has become an important part of congestion management [4]. The increasing of electricity trade and power flow uncertainty has limited the transmission of electrical energy obviously. Consequently, transmission congestion had become an important subject to be solved.

The transmission congestion of power system means that the requirements of power transmission can't be satisfied because of the limitation of its transmission capacity, which usually includes transmission lines or transformer active power flow exceeding the permitted limit and the node voltage off-limit, etc. In order to eliminate the congestion, the management mode of congestion presents diversification. In the traditional congestion management mode, power grid companies adjust power plant power plan, and generator outputs to invoke a high power. This kind of congestion management usually concentrates on the side of power generation. Literature [5] proposes a congestion management model of joint mode; its essence is to consider all kinds of security constraints of the Optimal Power Flow (OPF) problems. Due to the fluctuation of node electricity price under this model is very big, and trade surpluses can be produced, which produce wrongful stimulate to the Independent System Operator (ISO). Therefore the PJM energy market in the United States and electricity market in the New England use financial transmission rights to solve the transmission congestion [6]. User demand elasticity is also used to solve the transmission congestion. Under the market structure of both sides of supply and demand quoting at the same time, the load of each node is a decision variables affected by price, ISO can control electricity to ease congestion flexibly. Literature [7] structures congestion management model with the method of sensitivity analysis. Literature [8] uses generator rescheduling to solve the congestion, and provides a kind of congestion cost allocation method.

Using IL (Interruptible Load) to solve the congestion management is a new solution of the congestion management in recent years. IL can make full use of the electricity elasticity, eliminate or relieve congestion and the power supply tension in peak load. According to the interruptible power supply contract signed by the power company and power users [9], it allows power companies to remove part of the user load as the contracted purview at a particular period of time (such as peak load). Meanwhile giving the user certain power shortage compensation can reduce the electricity load during peak hours to relieve the tense situation of power supply, thus achieve the purpose of congestion management.

2.3 Historical and Evolution Perspective

Despite their relative simplicity, Power System Stabilizers (PSS) may be one of the most misunderstood and misused pieces of generator control equipment. The ability to control synchronous machine angular stability through the excitation system was identified with the advent of high speed exciters and continuously-acting voltage regulators. By the mid-1960"s several authors had reported successful experience with the addition of supplementary feedback to enhance damping of rotor oscillations. Since the early1960s, power system stabilizers have been considered as integral components of the excitation systems installed on all large generators on the Ontario Hydro system. The use of these PSS units continues to produce millions of dollars of annual benefits [10].

2.4 PSS Design Concepts

The developments in the area of PSS in the power systems have been discussed through the various PSS system designs methods. Most of the PSS designs are based on the application of techniques developed in the area of control system designs. Recently, heuristic search algorithms such as genetic algorithm (GA) have been applied to the problem of PSS design [10]. Supplementary constant output produced to improve stability while the operating condition changes and is always suited to operating conditions. Particle Swarm Optimization (PSO) technique was developed by Eberhart and Kennedy [10] which was inspired by the Social behavior of Bird flocking and fish schooling. The results show the potential of PSO technique for optimal design of PSS and can work effectively over a wide range of loading conditions and system configurations. The performance of the proposed PSOPSSs is compared to that of GAPSSs It is clear that the system performance with the proposed PSOPSSs is much better than that of GA-PSSs and the oscillations are damped out much faster than CPSS.

The PSS designed using conventional method performs well around the nominal operating condition. However, its performance degrades as the system becomes more loaded [5].Breeder Genetic Algorithm, BGAPSS performs slightly better than the GA-PSS. GA however has some limitations such as premature convergence, difficulties in selecting optimal genetic operators as well as the high computational capacity required in solving complex optimization problems. In order to deal with some of the limitations, BGA was proposed by John Greene [10].This paper uses a slightly different version of BGA known as adaptive mutation BGA.

The transient stability of a power system is a nonlinear property and cannot be understood and properly addressed using linear analysis. Nonlinear controller, inspired and designed using the nonlinear Hopf bifurcation theory, can give great insight into the understanding and improving the transient stability margins of the power system. Hopf bifurcation (HB) is a nonlinear theory that is useful in explaining some of those phenomena [10].Existence of a HB in a system can be inferred using the linearized model of the system. This has been used, for instance, in [10], a new technique based on PSO is proposed to optimize the parameters settings of CPSS is developed and Simulation results show the effectiveness and robustness of the proposed OPSS over CPSS.

Artificial Bee Colony proposed by Karaboga [10] is a new technique proposed to optimize the parameters settings of CPSS. PSS parameters settings are computed using linear control theory [10]. Simulation results show the effectiveness and robustness of the proposed ABCPSSs over CPSSs. Another version of ABC is Interactive ABC, Investigations reveal the performance of IABC based multiband power system stabilizers in a multi machine infinite bus system is better in terms of settling time and peak overshoot under fault conditions and provide good damping characteristics during small disturbance and large disturbances for local as well as inter area modes of oscillations [10].

CHAPTER THREE

MODELING OF TCSC AND PSS DESIGN CRITERIA

3.1 Thyristor Controlled Series Capacitor (TCSC)

The TCSC operates as a series controlled reactance, whose objective is to compensate the transmission line impedance. The high switching speed of the TCSC provides a mechanism to control the power flow in the transmission lines, which allows increasing the load with the existing grid and the damping in the interconnection of large power systems, and also provides the possibility of quick power flow adjustment in response to several contingencies that may occur in the system. The TCSC can also regulate the steady-state power flow to keep it within the system physical limits [15, 16].

The TCSC can be modeled as a variable reactance (X_{TCSC}) in series with the transmission line. The variation of X_{TCSC} allows regulating the active power flow through the line, increasing the damping of power oscillations, among other benefits.

The modeling of a TCSC can be composed by different control types which allow the following functions [16]:

- Control of active power flow through the line and enhance the small signal stability of the system.
- Improvement of transient stability.
- Limiting short-circuit currents.

From these types of control strategies, the controller that allows the power flow control is modeled in this section. Figure 3.1 illustrates a block diagram of a control system designed for controlling power flows and increasing the damping, which is presented by Milano [17]. This diagram consists of a PI (Proportional integral) controller and a first-order delay. The purpose of this control is to modify the reactance of the transmission line in order to maintain a constant power flow. The output signal of the block diagram of the TCSC is its variable susceptance (b_{TCSC}), whose expression, as stated by Milano [17], is:

$$b_{TCSC}(XC) = - \frac{\frac{Xc}{Xkm}}{Xkm(1-\frac{XC}{Xkm})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

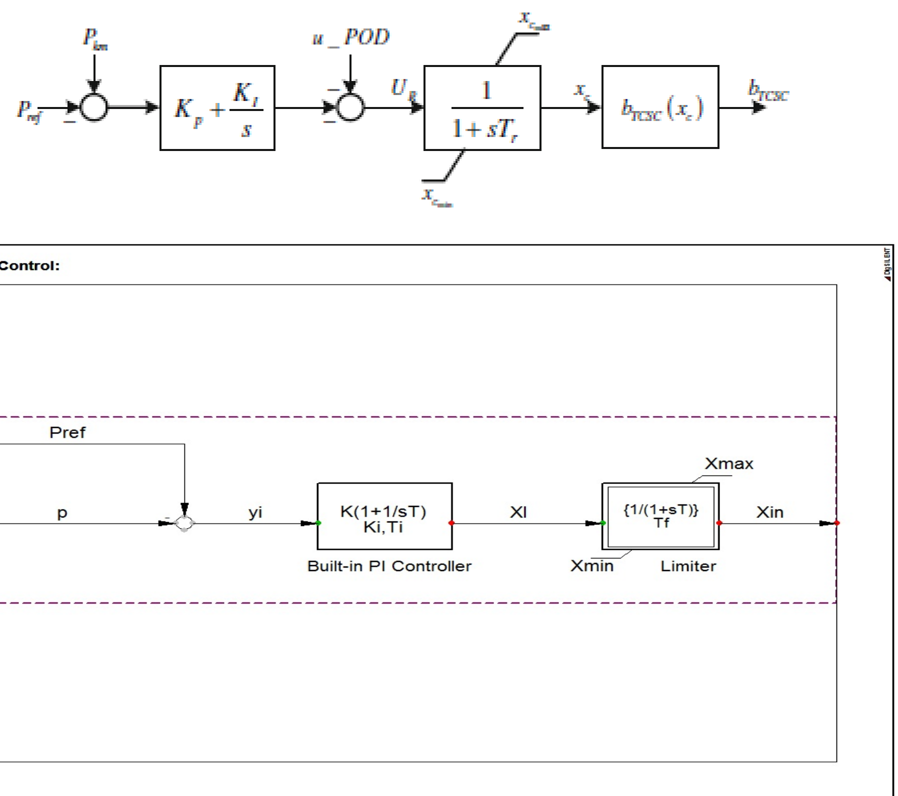

Fig (3.1): a block diagram of a control system designed for controlling power flow

Where:

P_{ref}:is the active power reference.

P_{km}: is the active power transmitted by the line between nodes k and m.

POD: is the power oscillation damper (POD) signal.

b_{TCSC}:is the susceptance of the TCSC.

x_c:is the control signal (output of the first order delay).

x_{km}:is the line reactance between nodes k and m.

K_p:is the proportional gain of the PI controller.

K_I:is the integral gain of the PI controller.

$T_{r:}$is the first order delay time constant.

The operation of the TCSC control system permits measuring the active power flow through the line (P_{km}) and comparing it with the active power reference (P_{ref}). Thus, when P_{km} is higher than P_{ref}, the control reactance xc is negative, which means that b_{TCSC} is positive. This means that the equivalent reactance of the line increases, causing a decrease of the transmitted active power (simulating the effect of increasing the line length). On the contrary, if P_{km} is lower than P_{ref}, then xc is positive, which means that b_{TCSC} is negative; therefore, the equivalent reactance of the line decreases causing an increase in the transmitted power (behaves as if the line length be shortened). TCSC implementation in DigSILENT Power Factory is performed through a fixed series capacitor in parallel with a controlled series reactor (Thyristor controlled reactor—TCR). For this configuration, the variable to be controlled is the value of the input reactance of the series reactor (xin) given in ohm [18]. Figure 3.2 shows the TCSC scheme in series with the line, whereas Fig. 3.3depicts the implementation in Power Factory.

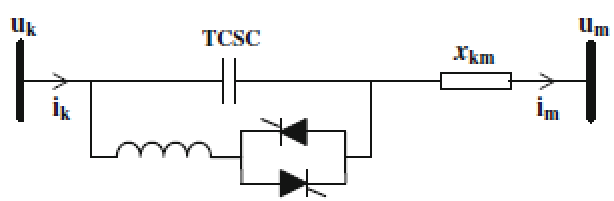

Fig (3.2): TCSC scheme in series with the line

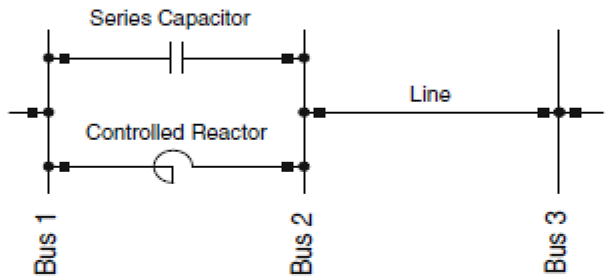

Fig (3.3): Implementation of TCSC in POWER FACTORY

Considering the scheme of Fig. 3.2, the total branch reactance (x_T) is as follows:

$X_T = X_{km} + X_{TCSC}$ ……………………… …... (3.2)

Besides, the x_{TCSC} reactance is the parallel equivalent between the capacitor and reactor reactance, and its expression is as follows:

$$j.X_{TCSC} = -j\frac{1}{bTCSC} = \frac{(-j.xcap).(j.xin)}{j.xin - j.xcap} = \frac{xcap.xin}{j(xin - xcap)} = -j\,\frac{xcap.xin}{(xin - xcap)} \quad \text{………. (3.3)}$$

Where:

x_{cap}: is the reactance of the fixed capacitor.

X_{in}:is the controlled reactance of variable reactor.

b_{TCSC}: is the total TCSC susceptance ($x_{TCSC} = 1/b_{TCSC}$).

From (3.3), and considering that x_{cap} is a priori defined (i.e. the fixed capacitor does not change its reactance, which is appropriately chosen during the design), it is possible to determine the expression that relates x_{in} as a function of b_{TCSC}

$$X_{in} = -\,\frac{xcap}{bTCSC.xcap - 1} \quad \text{…………………. (3.4)}$$

Since the reactor in parallel with the fixed capacitor might eventually make up together a resonance circuit, it is necessary to ensure that the x_{TCSC} does not surpass determined minimum and maximum thresholds. Thus, there is an operating zone where x_{TCSC} might acquire extremely high values (i.e. parallel resonance), which necessarily has to be avoided (i.e. not-allowed operating zone). Consequently, the requirement of limiting the TCSC operating zone, so that $x_{TCSC} \in [x_{TCSCmin}, x_{TCSCmax}]$, has to be considered in the TCSC controller design. This fact highlights the requirement of specifying a limit of line compensation. Therefore, in order to ensure the system stability, it is recommended to compensate up to a maximum compensating fraction (CF) of the line reactance nominal value (x_{km}), both in the capacitive (CFcap) and inductive (CFind) TCSC operating zones. Therefore, X_{TCSC} will be in the range given by (3.5).

$$-CF_{cap}.x_{km} \leq x_{TCSC} \leq CF_{ind}.\ x_{km} \quad \text{.............................} \quad (3.5)$$

Based on system experiences, a rational CF might be 0.3 (30 % of x_{km}).

From (3.5), it is easy to determine that the TCSC susceptance b_{TCSC} will satisfy The following relations:

$$b_{TCSC} \leq -\frac{1}{CFind.xkm} \quad \text{and} \quad b_{TCSC} \geq \frac{1}{CFcap.xkm} \quad \text{.......................} \quad (3.6)$$

Replacing (3.1) in (3.6), and after solving the in equations, the range of xc (output of the first-order delay) can be determined as follows:

$$\frac{xkm}{1+CFind} \leq x_c \leq \frac{xkm}{1-CFcap} \quad \text{.............................} \quad (3.7)$$

Therefore, the limits of the first-order delay X_{cmax} and X_{cmin} are as follows:

$$X_{cmin} = \frac{xkm}{1+CFind} \quad \text{and } Xcmax = \frac{xkm}{1-CFcap} \text{..........................} \quad (3.8)$$

These last presented limits allow ensuring the line compensation does not exceed the pre-defined thresholds, and also, the TCSC actually operates outside the not allowed zone.

As explained beforehand, in DigSILENT POWERFACTORY, the TCSC is implemented via the adequate control of the input reactance of the series reactor (x_{in}) [18]. Thus, x_{in} is the signal to be controlled (i.e. the required output of the DSL model of the controllers). Then, it is necessary to replace the last block of the controllers (i.e. the block that computes b_{TCSC} from the control signal xc, shown in Fig. 3.1) by a block that allows establishing the relationship between the control signal xc and x_{in}(i.e. the available signal to be controlled in the POWER FACTORY object). For this purpose, the existence equivalency between (3.1) and the inverse of (3.3) can be used, as shown by (3.9).

$$-\frac{\frac{xc}{xkm}}{(1-\frac{xc}{xkm})} = \frac{xin-xcap}{xcap.xin} \quad \ldots\ldots (3.9)$$

After several simplifications, it is possible to obtain from (3.9), the expression that relates x_{in} with the control signal xc, as follows:

$$X_{in} = \frac{xcap.xkm-xcap.xc}{\frac{xcap.xc}{xkm}+xkm-xc} \quad \ldots\ldots (3.10)$$

This last expression is introduced in a block called TCSC-Xin Interface. b_{TCSC}(xc). It is worth mentioning that, while x_{cap}, x_{km} and xc are in per unit, x_{in}has to be in ohm (since it is the signal specification of the reactor reactance in Power Factory); thus, (3.10) has to be additionally multiplied by the base impedance (z_{base}).

3.2 PERFORMANCE INDICES CALCULATION

The optimal locations to install the FACTS devices for secured Power flow under normal and contingency condition are presented in this section. The overload on the transmission line is eliminated by placing TCSC in the appropriate location.

Active power performance index (PIp) is introduced in this section for installing TCSC at suitable location to achieve secured power flow under normal operating condition. The essential idea of TCSC placement in the proposed methodology is to determine a line, which is most suitable for eliminating the overloads on the transmission lines.

3.2.1 Active power performance index (PIp)

$$\text{Pip} = \left(\frac{Pi}{Pmax}\right)^{2n} \quad \ldots\ldots (3.11)$$

Where:

Pi=Active power flow in line i.

P_{max}=Maximum power flow in line i

n=specified exponent (Here value of n is kept unity)

Maximum power transfer can be expressed by formula:

$$P_{max} = \frac{Vi*Vj}{X} \quad \text{……} (3.12)$$

Where:

V_i=Voltage at bus i obtained from power flow

V_j=Voltage at bus j obtained from power flow

X=Reactance of line connecting bus i and bus j

PIp value is calculated for all the lines .the line with least positive value is considered and ranked first. Next least valued is second and so. TCSC is placed on line having rank 1.

3.2.2 Contingency capacity Performance index (CPI)

Contingency capacity Performance index (CPI) is introduced in this section for installing TCSC at suitable location to achieve secured power flow under contingency condition. Contingency capacity performance index is calculated as follows:

$$CPI= \frac{Pmax-Pi}{Pmax} \quad \text{……} (3.13)$$

Where:

Pi=Active power flow in line i

CPI value is calculated for all the lines .the line with highest positive value is considered and ranked first. Next highest valued is second and so. TCSC is placed on line having rank 1.

3.3 Power System Stabilizer Design

The problem of power system stabilizer design is to determine the parameters of the stabilizer so that the damping of the system's electromechanical modes is increased. This must be done without adverse effects on other oscillatory modes, such as those associated with the exciters or the shaft torsional oscillations. The stabilizer must also be designed so that it has no adverse effects on a system's recovery from a severe fault. Some of the most recent power system stabilizers have additional lead/lag blocks [19].

3.3.1 Design Approach

Two methods can be following to determine the PSS Parameters:

1. Traditional method (calculated method).
2. Modern method (Optimization method)

Calculated Method:

The contribution of the PSS to the torque-angle loop (assuming $\Delta V_{ref} = 0$ and $\Delta\delta = 0$) is shown in figure 3.4 [20]:

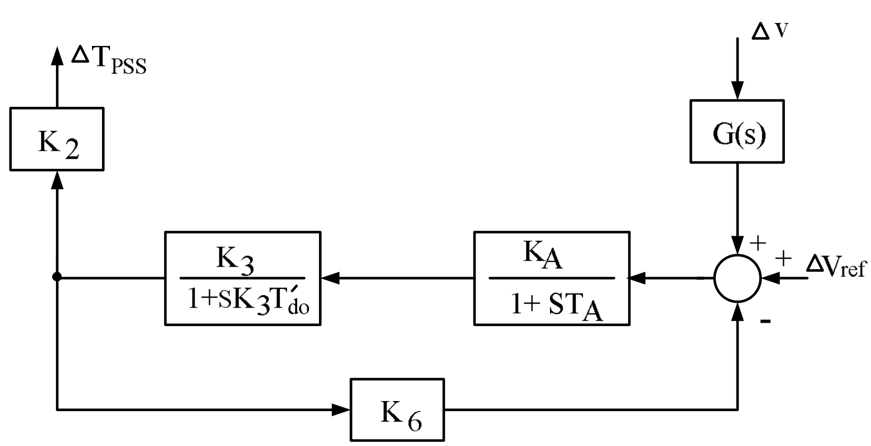

Figure (3.4): the contribution of the PSS to the torque-angle loop

From figure 3.4:

$$\frac{\Delta T_{PSS}}{\Delta v} = \frac{G(s)K_2K_AK_3}{K_AK_3K_6+(1+sT_{do}K_3)(1+sT_A)} \text{ ....}(3.14)$$

$$\frac{\Delta T_{PSS}}{\Delta v} = G(s)\ GEP(s)$$

$$G(s) = K_{PSS}\frac{(1+sT_1)(1+ST_3)\ sT_w}{(1+sT_2)(1+sT_4)(1+sT_w)} = K_{PSS}G_1(S) \text{ .... }(3.15)$$

$$GEP(S) = \frac{K_2K_AK_3}{K_AK_3K_6+(1+sT_{do}K_3)(1+sT_A)} \text{ .... }(3.16)$$

The PSS parameters based on calculated method is summarized below:

1. Select $T_2 = 0.05$, $\zeta = 0.2$.
2. Calculate ω_n from $\omega_n = \sqrt{\frac{K_1\omega_s}{2H}}$.
3. Calculate GEP at S = $j\omega_n$ from equation (3.16)
4. Let X = angle (GEP).
5. Also let Y = angle ($1+j\omega_n T_2$).
6. Then let Z = Y-X
7. $T_1 = \frac{\tan(Z)}{\omega_n}$
8. Prepare G1 from $G_1 = \frac{1+j\omega_n T_1}{1+j\omega_n T_2}$
9. Then $K_{PSS} = \frac{4H\zeta\omega_n}{|GEP||G_1|}$
10. Select $T_3 = T_1$, and $T_4 = T_2$
11. Select $T_w = 10$ seconds.

The PSS should be activated only when low-frequency oscillations develop and should be automatically terminated when the system oscillation ceases.

The washout stage has the transfer function $G_w = \frac{sT_w}{1+sT_w}$ since the washout filter should not have any effect on phase shift or gain at the oscillating frequency, it can be achieved by choosing a large value of T_w so that $sT_w$is much larger than unity. Hence, its phase contribution is close to zero. The PSS will not have any effect on the steady state of the system since, in steady state [21].

CHAPTER FOUR

MODERN METHODS OF OPTIMIZATION

4.1 Introduction

Optimization is the act of obtaining the best result under given circumstance-s. In design, construction, and maintenance of any engineering system, engineers have to take many technological and managerial decisions at several stages. The ultimate goal of all such decisions is either to minimize the effort required or to maximize the desired benefit. Since the effort required or the benefit desired in any practical situation can be expressed as a function of certain decision variables, optimization can be defined as the process of finding the conditions that give the maximum or minimum value of a function [11].

In recent years, some optimization methods that are conceptually different from the traditional mathematical programming techniques have been developed. These methods are labeled as modern or nontraditional methods of optimization. Most of these methods are based on certain characteristics and behavior of biological, molecular, swarm of insects, and neurobiological systems [11].The most important methods mentioned below:

1. Genetic algorithms
2. Simulated annealing
3. Particle swarm optimization
4. Ant colony optimization
5. Fuzzy optimization
6. Neural-network-based methods

Most of these methods have been developed only in recent years and are emerging gas popular methods for the solution of complex engineering problems. Most require only the function values (and not the derivatives). The genetic algorithms are based on the principles of natural genetics and natural selection. Simulated annealing is based on the simulation of thermal annealing of critically heated solids. Both genetic algorithms and simulated annealing are stochastic methods that can find the global minimum with a high probability and are naturally applicable for the solution of discrete optimization problems. The particle swarm optimization is based on the behavior of a colony of living things, such as a swarm of insects, a flock of birds, or a school offish. Ant colony optimization is based on the cooperative behavior of real ant colonies, which are able to find the shortest path from their nest to a food source. In many practical systems, the objective function, constraints, and the design data are known only in vague and linguistic terms. Fuzzy optimization methods have been developed for solving such problems. In neural-network-based methods, the problem is modeled as a network consisting of several neurons, and the network is trained suitably to solve the optimization problem efficiently [12].

4.2 PARTICLE SWARM OPTIMIZATION

4.2.1 Introduction

Particle swarm optimization, abbreviated as PSO, is based on the behavior of a colony or swarm of insects, such as ants, termites, bees, and wasps; a flock of birds; or a school of fish. The particle swarm optimization algorithm mimics the behavior of these social organisms. The word particle denotes, for example, a bee in a colony or a bird in a flock. Each individual or particle in a swarm behaves in a distributed way using its own intelligence and the collective or group intelligence of the swarm. As such, if one particle discovers a good path to food, the rest of the swarm will also be able to follow the good path instantly even if their location is far away in the swarm. Optimization methods based on swarm intelligence are called behaviorally inspired algorithms as opposed to the genetic algorithms, which are called evolution-based procedures. The PSO algorithm was originally proposed by Kennedy and Beernaert in1995 [12].

In the context of multivariable optimization, the swarm is assumed to be of specified or fixed size with each particle located initially at random locations in the multidimensional design space. Each particle is assumed to have two characteristics: a position and a velocity. Each particle wanders around in the design space and remembers the best position (in terms of the food source or objective function value) it has discovered. The particles communicate information or good positions to each other and adjust their individual positions and velocities based on the information received on the good positions [12].

As an example, consider the behavior of birds in a flock. Although each bird has a limited intelligence by itself, it follows the following simple rules:

1. It tries not to come too close to other birds.
2. It steers toward the average direction of other birds.
3. It tries to fit the “average position” between other birds with no wide gaps in the flock. Thus the behavior of the flock or swarm is based on a combination of three simple factors:

a. Cohesion—stick together.
b. Separation—does not come too close.
c. Alignment—follows the general heading of the flock.

The PSO is developed based on the following model:

i. When one bird locates a target or food (or maximum of the objective function), it instantaneously transmits the information to all other birds.
ii. All other birds gravitate to the target or food (or maximum of the objective function), but not directly.
iii. There is a component of each bird's own independent thinking as well as its past memory. Thus the model simulates a random search in the design space for the maximum value of the objective function. As such, gradually over much iteration, the birds go to the target (or maximum of the objective function) [12].

4.2.2 Computational Implementation of PSO

After all parameters of the particle swarm optimization determined as in table (4.1) the velocity and position of particle j in the i^{th} iteration can be calculated and updated respectively as follow and as in flowchart in figure 4.1:

$$V_j(i) = V_j(i-1) + c_1 r_1 [P_{best,j} - X_j(i-1)] + c_2 r_2 [G_{best} - X_j(i-1)] \quad \ldots\ldots\ldots\ldots (4.1)$$

$$X_j(i) = X_j(i-1) + V_j(i); \quad \ldots\ldots\ldots\ldots (4.2)$$

$j = 1, 2 \ldots N$

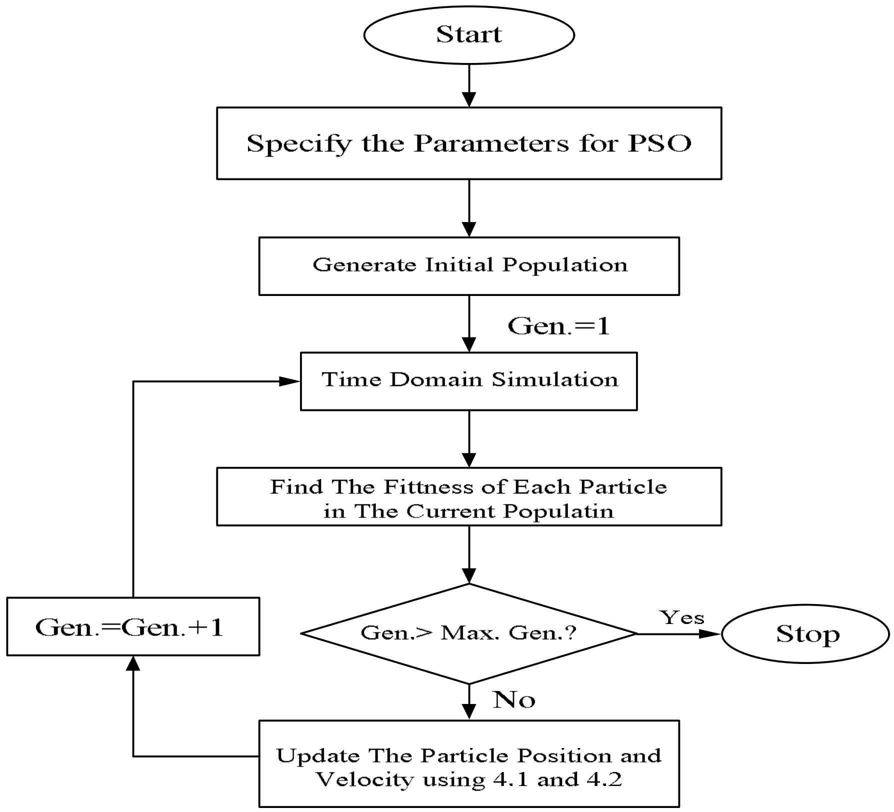

Figure (4.1): Flowchart of particle swarm optimization algorithm

Particle:

The “particle” is defined as a vector that contains the desired variables to be optimized. There is a trade-off between the number of particles and the number of iterations of the swarm, and the fitness value of each particle has to be evaluated using a user-defined function at each iteration. Thus, the number of particles should not be large because computational effort could increase dramatically. Swarms of 5-20 particles are normally chosen as appropriate population sizes [13].

Fitness Function:

The PSO fitness function used to evaluate the performance of each particle corresponds to a user-defined objective function [13].

4.3 PSS Parameter optimization applying PSO

4.3.1 Optimization problem

The problem here is on setting the optimal parameter of the PSS using PSO. This results in the minimization of the critical damping index (CDI), which is defined by:

$$\text{CDI} = \text{J} = (1-\xi)\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

$$\xi_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2+\omega_i^2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.4)$$

Equation 4.4 is the damping ratio of the i^{th} critical swing mode. The objective of the optimization is to maximize the damping ratio (ζ) as much as possible. There are three tuning parameters of the PSS namely, the controller gain (K_{STAB}), lead and lag time constants (T_1 and T_2), these parameters are to be optimized by minimizing the desired objective function "J" given in Equation 4.3. With a change of parameters of PSS, the damping ratio (ζ) as well as J varies. The problem constraints are the bounds on the controller parameters [13, 14]. The optimization problem can then be formulated as follows:

Minimize J as in 4.3

Subject to

$$K_{PSS}^{min} \leq K_{PSS} \leq K_{PSS}^{max}$$

$$T_1^{min} \leq T_1 \leq T_1^{max}$$

$$T_2^{min} \leq T_2 \leq T_2^{max}$$

4.3.2 Typical values of the PSS parameters are

K_{PSS} is in the range of 0.1 to 50.

$T_1$is the lead time constant, 0.2 to 1.5 sec.

$T_2$is the lag time constant, 0.02 to 0.15 sec.

$T_3$is the lead time constant, 0.2 to 1.5 sec.

$T_4$is the lag time constant, 0.02 to 0.I5 sec [8].

CHAPTER FIVE

SIMULATION AND RESULTS DISCUSSION

5.1 Introduction

All the simulation in this chapter was carried out using DIG SILENT (POWER FACTORY) software and MATLAB m-file environment. First all four PSS found in Sudanese National Grid were activated and retuned using PSO code (see appendix A). In the second step optimal location for TCSC under normal operating condition was defined using power performance index to reduce transmission lines loading. Then after placing TCSC in the grid the damping ratios was compared when there is PSS and TCSC with the case without them. Also the improvement of the transmission lines loading was stated. In the last step contingency performance index was used to define optimal location for TCSC under contingency condition which improves system performance under contingency condition.

5.2 Power System Stabilizers Parameters after PSO Tuning

All four PSSs found in Sudanese national grid were activated and tuned again using PSO code (see appendix A). The tuning process done through linking PSO code (MATLAB – m-file) with DIGSILENT (Power Factory) software. The parameters of the PSSs illustrated in table (5.1) and the graph of PSO tuning process represented in figure (5.1)

Table (5.1): PSS parameters after tuning using PSO

PSS NO	K	T_1	T_2	T_3	T_4	T_w
1	36.794	2.259	1.6525	2.4949	0.33233	20
2	27.118	1.5949	1.4804	0.70887	1.8694	20
3	21.42	1.7307	1.1606	2.2165	1.5258	20
4	39.71	1.7148	1.2833	1.6195	0.9045	20

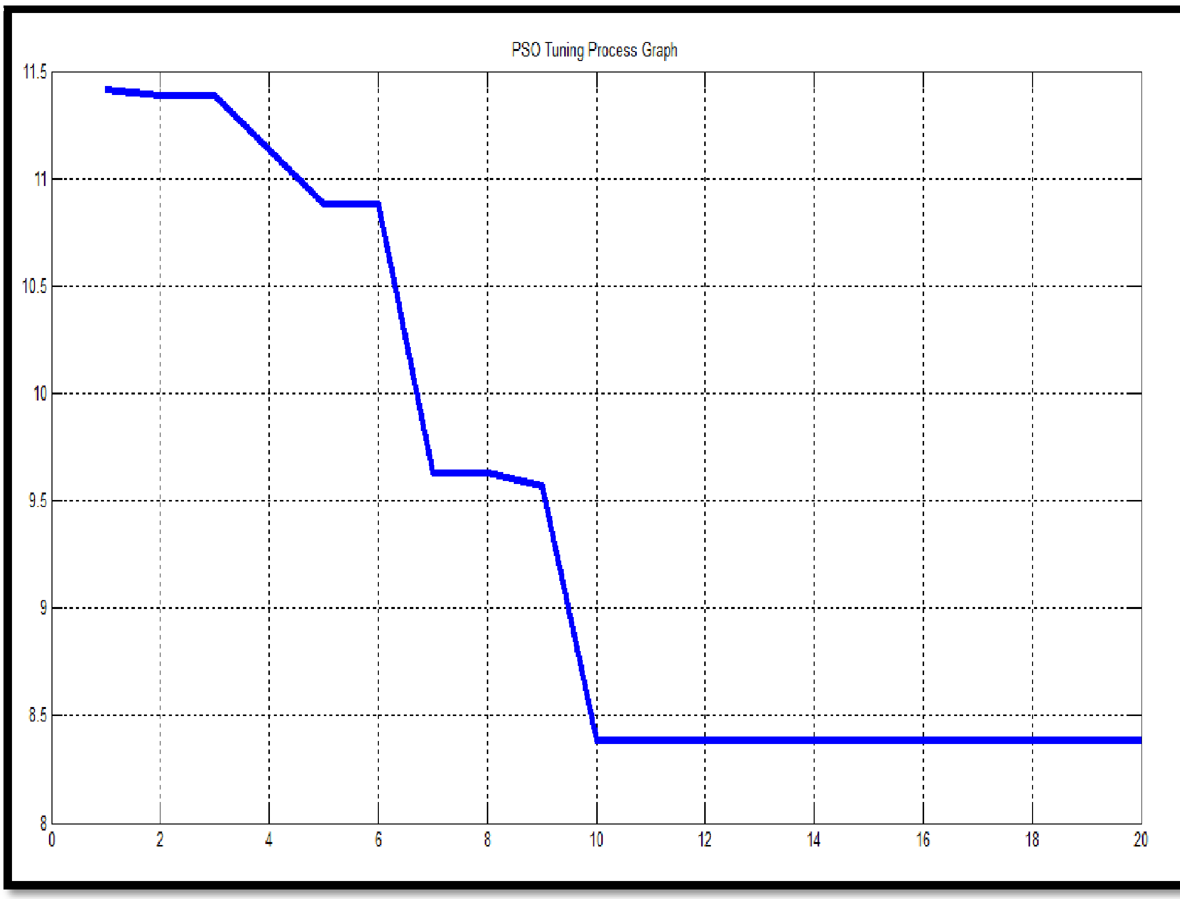

Figure (5.1): PSO tuning process graph

5.3 TCSC Optimal Location under Normal condition calculations:

Table (5.2): Ranking based on active power performance index (PIp).

Line NO	Pi(MW)	Vi(KV)	Vj(KV)	Reactance (Xi) ohm	Pmax	Pip	Ranking
1	149.9	229	227.4	6.961825	7480.021	0.000401604	50
2	68.5	227.4	226.1	28.06895	1831.744	0.001398464	63
3	34.6	226.1	223.8	28.08507	1801.711	0.000368792	49
4	70.5	228.8	223.8	28.08507	1823.226	0.001495192	66
5	94	209.8	223.8	25.066	1873.184	0.002518226	69
6	91.8	203.5	209.8	30.95	1379.46	0.004428604	72
7	77	520.4	526.1	65.3292	4190.813	0.000337586	47
8	24.6	231.4	230.4	21.14	2521.975	9.51456E-05	39
9	58.2	230.2	231.4	17.365	3067.566	0.000359963	48
10	94.1	230.2	230	0.755	70127.15	1.80056E-06	11
11	20.4	230	227.2	9.059999	5767.771	1.25096E-05	24
12	106.5	225.8	227.2	2.114	24267.63	1.92595E-05	28
13	241.8	225.8	227.2	4.228	12133.81	0.000397117	51
14	242	224.9	224.8	0.453	111606	4.70171E-06	16
15	165.6	223.2	224.8	6.493	7727.608	0.00045923	52
16	194.5	223.2	223.8	8.304999	6014.71	0.001045707	60
17	175.3	236.8	223.8	71.734	738.7827	0.056302849	79
18	4.2	540.6	520.4	95.49599	2945.969	2.03255E-06	12
19	135.4	232	230.6	3.0955	17282.89	6.13768E-05	33
20	136.3	227.9	230.6	5.738	9158.895	0.000221465	45
21	260.1	227.9	227.1	5.738	9019.883	0.000831532	59
22	567.2	227.1	240.2	22.3027	2445.866	0.053778298	77
23	7	240.2	240	16.1872	3561.332	3.86341E-06	15
24	57.1	240.2	254	12.684	4810.06	0.00014092	43
25	52.3	254	265.3	11.8233	5699.441	8.42052E-05	37
26	45.9	265.3	281.3	19.026	3922.469	0.000136932	42

27	22.8	281.3	291.3	13.892	5898.552	1.4941E-05	25
28	14.9	291.3	296.9	9.966	8678.203	2.9479E-06	14
29	10.8	296.9	304.3	18.12	4986.019	4.6918E-06	17
30	3.4	304.3	306.3	11.929	7813.487	1.89351E-07	5
31	40.1	240.7	240.2	24.6583	2344.693	0.000292494	53
32	91.5	240.7	240.2	26.0928	2215.789	0.001705239	68
33	9.6	238.5	241.6	71.734	803.2676	0.000142831	57
34	189.6	241.6	236.8	10.075	5678.499	0.001114832	64
35	15.9	540.6	538.1	10.1568	28640.6	3.08198E-07	6
36	22.3	230.2	230.2	3.926	13497.72	2.72954E-06	13
37	6.3	227.2	230.2	4.53	11545.57	2.97749E-07	7
38	68.2	106.7	105.9	1.441	7841.45	7.56443E-05	35
39	22.6	106.7	106.7	1.614	7053.835	1.02652E-05	21
40	71	106.7	105.6	1.614	6981.115	0.000103435	40
41	3.5	105.6	105.6	1.076	10363.72	1.14053E-07	3
42	154.4	227.3	232	6.191	8517.784	0.00032858	46
43	76.1	105.6	104.4	1.25085	8813.719	7.45506E-05	34
44	121.7	106	104.2	2.21925	4976.997	0.000597925	58
45	5.5	104.4	104.2	0.79355	13708.63	1.60967E-07	4
46	27.9	105.7	106.7	2.7667	4076.405	4.6844E-05	32
47	154.9	105.7	106.7	0.6795	16597.78	8.70969E-05	38
48	82	105.7	105.4	0.4304	25884.71	1.00355E-05	22
49	67.7	104	103.8	0.4035	26753.9	6.40329E-06	19
50	50.4	103.8	102.9	1.883	5672.342	7.89471E-05	36
51	87.5	104	103.7	0.4035	26728.13	1.07171E-05	23
52	2.1	103.7	103.6	1.0491	10240.51	4.20528E-08	2
53	19.4	103.6	103.6	1.4795	7254.451	7.15145E-06	20
54	56.2	104.2	103.6	1.0222	10560.67	2.83198E-05	30
55	83.1	105.7	103.6	4.842	2261.57	0.00135015	61
56	195.7	224.8	227.1	5.587	9137.655	0.000458682	54
57	71.2	104.7	104.3	0.6315	17292.49	1.69529E-05	27
58	34.5	104.3	104	1.263	8588.44	1.61365E-05	26

59	34.4	104	104	7.532	1436.006	0.000573858	56
60	2.8	105.9	105.2	1.076	10353.79	7.31336E-08	10
61	27.9	105.2	104.4	4.035	2721.903	0.000105066	41
62	15.8	105.2	104.7	32.417	339.7736	0.002162395	67
63	10.9	104.4	104.1	4.7685	2279.132	2.28725E-05	29
64	54.9	105.2	104.4	5.78875	1897.28	0.000837301	55
65	127.9	104.4	113.4	14.9455	792.1421	0.026069631	78
66	155.9	124.1	113.4	12.8826	1092.399	0.020367119	73
67	459.1	253.6	259	23.103	2843.025	0.026076741	76
68	45.5	259	270.2	22.68624	3084.769	0.000217559	44
69	0	270.2	270.8	9.059999	8076.177		
70	43.3	270.2	273.1	9.44354	7813.979	3.07066E-05	31
71	12	273.1	273.2	7.37937	10110.74	1.40863E-06	9
72	16.7	273.1	274.5	11.2495	6663.936	6.28017E-06	18
73	0	274.5	274.9	6.610779	11414.7		
74	4.1	111.2	111.5	0.52625	23560.67	3.02826E-08	1
75	15	111.2	105.6	29.049	404.2384	0.001376916	62
76	0.3	111.5	111.4	40.416	307.3313	9.5286E-07	8
77	39.9	104.4	105.5	14.735	747.4856	0.002849313	71
78	52.5	111.2	105.5	25.26	464.4339	0.012778233	74
79	220.9	259	247.4	33.22	1928.856	0.013115709	75
80	213.7	247.4	241.6	13.59	4398.222	0.002360776	70
81	71	228.8	229	28.06895	1866.66	0.001446725	65

From table (5.2) it observed that transmission line 74 (line from SNJA to SNAR) is having least Pip value 3.02826E-08 so ranked first. Table (5.2) provides optimal solution for optimal placement of TCSC in line 74 (rank 1). However this improvement in transmission lines overloading represented in table (5.3).

Table (5.3): Line data with TCSC and without TCSC under normal condition

Line NO	Loading without TCSC	Loading with TCSC
1	22.70%	22.60%
2	10.70%	10.70%
3	7.10%	7.10%
4	12.60%	12.60%
5	31.40%	31.30%
6	100.17%	99.70%
7	7.70%	7.90%
8	8%	9.20%
9	14.60%	13.90%
10	20.70%	25.10%
11	15.30%	7.90%
12	39.30%	24.90%
13	49.40%	44.60%
14	49.50%	44.50%
15	36.70%	34.80%
16	37.50%	40.70%
17	50.90%	62.90%
18	11.60%	12.90%
19	35.30%	30.90%
20	37.40%	32.90%
21	51.60%	48%
22	100.82%	96.87%
23	4.70%	4.80%
24	52.90%	54%
25	46.60%	47.70%
26	43.50%	44.40%
27	36%	36.70%
28	27.40%	27.90%
29	24%	24.40%
30	8.10%	8.20%
31	10.20%	12.20%
32	21.50%	17.10%
33	7.00%	41.50%
34	29.50%	20.60%

35	5.70%	5.80%
36	4.90%	11.30%
37	29.40%	21.70%
38	17.80%	17.00%
39	4.90%	6.00%
40	19.20%	16.70%
41	1.60%	3.20%
42	77.30%	77.70%
43	24.30%	21.80%
44	29.30%	29.50%
45	5.80%	3.10%
46	23.00%	14.70%
47	46.30%	41.90%
48	21.40%	21.10%
49	17.60%	17.30%
50	13.50%	13.30%
51	24.30%	23.90%
52	1.80%	1.50%
53	4.60%	4.50%
54	33.00%	30.80%
55	19.20%	19.10%
56	38.10%	34.40%
57	70.20%	74.90%
58	60.60%	64.00%
59	15.70%	16.70%
60	28.60%	10.80%
61	13.80%	13.00%
62	27.90%	28.30%
63	12.90%	11.80%
64	29.10%	20.20%
65	85.90%	72.20%
66	38.10%	39.40%
67	81.40%	71.70%
68	50.70%	64.70%
69	75.20%	6.80%
70	18.50%	23.20%
71	3.90%	4.80%
72	10.00%	12.40%
73	4.20%	5.00%
74	10.60%	15.09%

75	24.40%	25.00%
76	2.40%	20.70%
77	65.20%	15.30%
78	73.20%	62.60%
79	75.20%	36.40%
80	39.30%	11.50%
81	11.50%	11.50%

Table (5.3) shows that placement of TCSC in the line between SNJA and SNAR decrease overloading of overloaded lines (L6 and L22) from **100.17%** and **100.82%** to **99.7%** and **96.87%** respectively. Also other lines having overloading within limits.

5.4 The Effects of adding PSSs and TCSC on the Dynamic Stability in Sudanese National Grid

5.4.1 Damping Ratio Improvement

The activation and tuning process of all PSSs found in Sudanese National grid has a significant role in enhancing system damping. However this improvement of system damping represented in table (5.4) and in the figure (5.2)

Table (5.4): System damping ratio comparison

Mode NO	Damping ratio without PSS and TCSC	Damping ratio with PSS + TCSC
1	0.132350806	0.144496
2	0.165021453	0.176
3	0.145564594	0.164699
4	0.103758697	0.117054
5	0.338732153	0.499738022
6	0.13549173	0.705348
7	0.712260435	0.702957509
8	0.164911037	0.16666598
9	0.341364858	0.35774

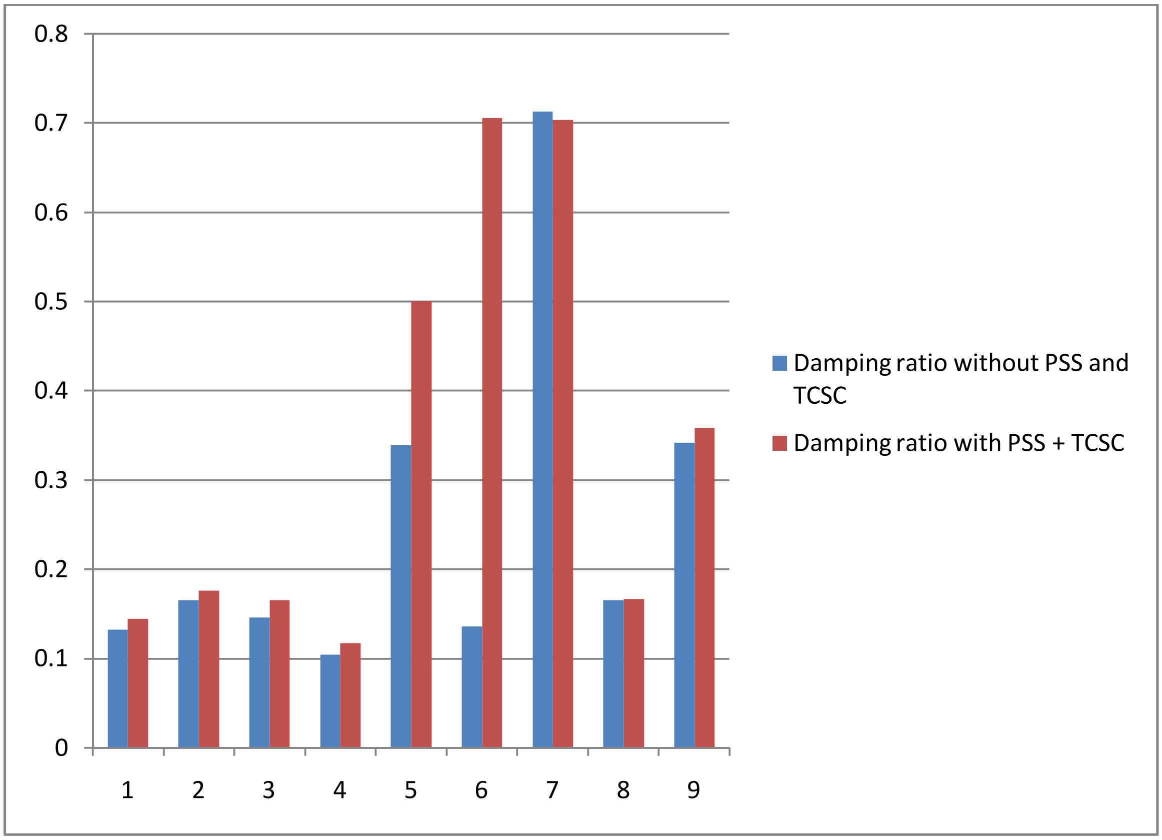

Figure (5.2): Comparison of system damping ratio

5.4.2 The Effects of Adding PSSs and TCSC on Eigen Values

The process of activating the PSSs and connecting TCSC in optimal location makes system Eigen values shifted towards stable region more than in the primitive case (without PSSs and TCSC). These results represented in table (5.5) also in figure (5.3) and figure (5.4).

Table (5.5): Oscillatory modes egine values with and without PSS and TCSC

Oscillatory mode	**Without PSS and TCSC**		**With PSS and TCSC**	
	Real part	Imaginary part	Real part	Imaginary part
Mode 00001	-1.249881274	9.9090149448	-1.487969373	10.189642132
Mode 00002	-1.332733846	6.6981777899	-1.296141878	7.2455040021
Mode 00003	-1.241561514	12.281326147	-2.028232195	12.147434965
Mode 00004	-1.799528595	12.227575641	-1.494368139	12.678813687
Mode 00005	-0.556622413	4.5928536302	-1.253789450	3.8866462783
Mode 00006	-4.584606964	4.5069236555	-4.506464748	4.5288150778
Mode 00007	-2.903862231	17.280884688	-2.925433438	17.276513054
Mode 00008	-5.952026883	16.111847786	-6.158574728	16.07728505
Mode 00009	-0.098059675	-0.	-1.865479286	0.46304759455

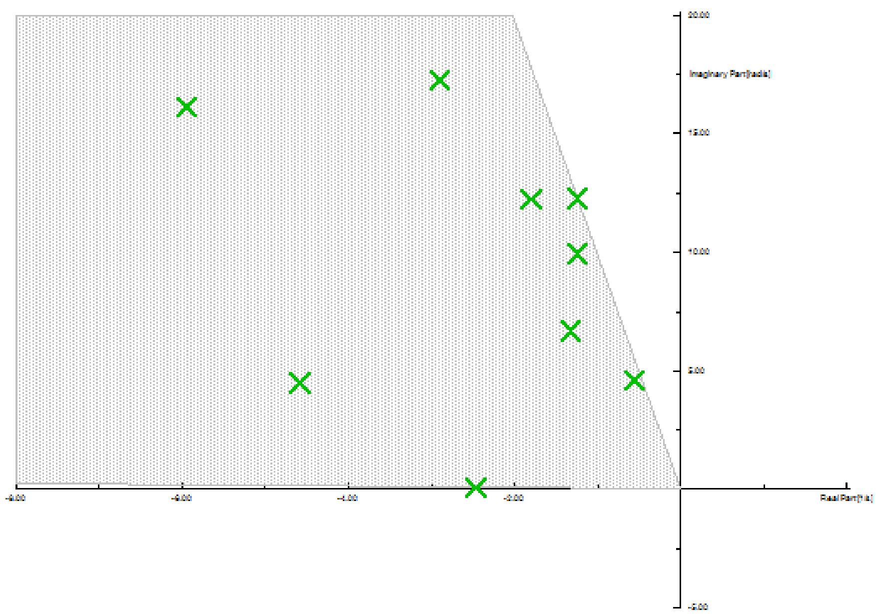

Figure (5.3): Eigen values plot without PSSs and TCSC

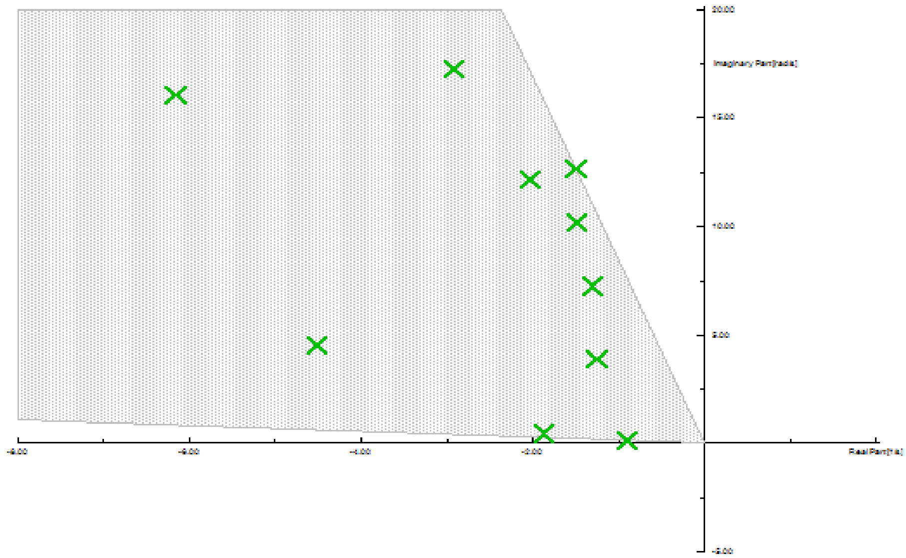

Figure (5.4): Eigen values plot with PSSs and TCSC

5.5 Implementation of TCSC in Sudanese National Grid under Contingency Condition

The contingency created by taking out the line 79 (from Gadarief to Hawata) and line 20 (from Gamoia to ALHuda). The contingency performance index (CPI) used to define optimal location for TCSC under contingency condition.

Table (5.6): Ranking based on contingency performance index (CPI).

Line NO	Pi(MW)	Vi(KV)	Vj(KV)	Reactance (Xi) ohm	Pmax	CPI	Ranking
1	149.9	228.6	228.4	6.961825	7499.792	0.980012779	55
2	68	225.7	227	28.06895	1825.287	0.962745592	65
3	34.6	225.7	223.3	28.08507	1794.505	0.980718921	54
4	69.9	223.3	228.4	28.08507	1815.973	0.961508232	68
5	94	209.4	223.3	25.066	1865.436	0.949609637	70
6	90.4	203	209.4	30.95	1373.447	0.934180229	72

7	83.6	519.6	524.8	65.3292	4174.031	0.979971397	56
8	18	229.8	230.4	21.14	2504.537	0.992813044	32
9	51.3	230.4	228.9	17.365	3037.061	0.983108668	50
10	94.4	228.9	228.9	0.755	69397.63	0.998639723	10
11	29.5	228.9	228.9	9.059999	5783.136	0.994898962	29
12	81.4	223.2	225.2	2.114	23777.03	0.996576528	24
13	214.7	223.2	221.3	4.228	11682.63	0.981622289	52
14	214.9	221.1	221.3	0.453	108012	0.998010406	16
15	136.3	216.6	221.1	6.493	7375.675	0.981520336	53
16	156.6	216.6	216	8.304999	5633.426	0.972201642	62
17	71.2	231.3	216	71.734	696.4731	0.897770636	74
18	22.2	537	519.6	95.49599	2921.853	0.992402081	34
19	122.4	228.7	230.2	3.0955	17007.51	0.992803178	33
20	123.3	225.5	228.7	5.738	8987.774	0.986281365	49
21	244.4	224.4	225.5	5.738	8818.787	0.972286438	61
22	550.4	239.3	224.4	22.3027	2407.732	0.771403111	76
23	7	239.2	239.3	16.1872	3536.162	0.998020453	15
24	57	239.3	253.1	12.684	4775.058	0.988062971	48
25	52.2	253.1	264.3	11.8233	5657.839	0.990773863	38
26	45.9	264.3	280.2	19.026	3892.403	0.988207799	47
27	22.8	280.2	290.2	13.892	5853.3	0.996104761	26
28	14.9	290.2	295.7	9.966	8610.49	0.998269553	13
29	10.8	295.7	303.1	18.12	4946.284	0.997816543	17
30	3.4	303.1	304.1	11.929	7726.776	0.999559972	42
31	28.9	293.3	239.6	24.6583	2849.94	0.989859436	6

32	21.7	237	239.6	26.0928	2176.279	0.99002885	42
33	67.7	233.9	237	71.734	772.7758	0.912393738	73
34	53	233.9	231.3	10.075	5369.833	0.990130047	40
35	10.5	534.5	537	10.1568	28259.54	0.999628444	4
36	29.2	228.9	228.6	3.926	13328.21	0.997809158	18
37	18.6	228.6	225.2	4.53	11364.4	0.99836331	12
38	68.2	106	105.2	1.441	7738.515	0.99118694	35
39	18.4	106	106.1	1.614	6968.154	0.997359415	21
40	75.9	106.1	104.9	1.614	6895.843	0.988993368	44
41	1.4	104.9	104.8	1.076	10217.03	0.999862974	2
42	154.1	225.6	230.2	6.191	8388.487	0.981629582	51
43	80.7	104.8	103.5	1.25085	8671.543	0.990693698	39
44	119.2	105	103.3	2.21925	4887.462	0.975611063	59
45	1	103.3	103.5	0.79355	13473.06	0.999925778	1
46	35.4	103	105.1	2.7667	3912.712	0.990952567	36
47	162.4	105.1	106.1	0.6795	16410.76	0.990104052	41
48	82	105.1	104.1	0.4304	25420.33	0.996774235	22
49	67.7	103	102.8	0.4035	26241.39	0.997420106	20
50	50.4	102.8	101.9	1.883	5563.101	0.990940305	37
51	87.8	103	102.7	0.4035	26215.86	0.996650882	23
52	2.3	102.6	102.7	1.0491	10043.87	0.999771005	3
53	17.4	102.6	102.6	1.4795	7115.079	0.99755449	19
54	58.2	103.3	102.6	1.0222	10368.4	0.994386791	30
55	80.8	102.6	104.6	4.842	2216.431	0.963545	64
56	198	224.4	221.1	5.587	8880.408	0.977703727	58

57	66.1	103	102.6	0.6315	16734.44	0.996050062	27
58	29.4	102.6	102.5	1.263	8326.603	0.996469148	25
59	29.3	102.5	103	7.532	1401.686	0.979096604	57
60	5.9	100.6	101.9	1.076	9527.082	0.999380713	7
61	27.9	100.6	99.8	4.035	2488.198	0.988787067	45
62	11.4	100.6	103	32.417	319.6409	0.96433498	63
63	10.9	96	96.4	4.7685	1940.736	0.994383574	31
64	65.4	100.6	96.4	5.78875	1675.291	0.960962003	69
65	306.4	108.5	96.4	14.9455	699.8361	0.562183185	78
66	413.6	108.5	138.4	12.8826	1165.634	0.645171722	77
67	496.6	288.3	294.9	23.103	3680.027	0.865055348	75
68	46.3	294.9	308.9	22.68624	4015.412	0.988469429	46
69	0	308.9	309.6	9.059999	10555.79		
70	43.3	308.9	312.5	9.44354	10221.93	0.995764011	28
71	12	312.5	312.7	7.37937	13242.15	0.999093803	8
72	16.8	312.5	314.4	11.2495	8733.721	0.998076421	14
73	0	314.4	314.7	6.610779	14966.72		
74	35.3	110	110	0.52625	22992.87	0.998464742	11
75	15	110	104.3	29.049	394.9534	0.962020832	66
76	0.3	110	109.9	40.416	299.1142	0.998997039	9
77	17.6	100.6	96.4	14.735	658.15	0.973258375	60
78	27.1	110	100.6	25.26	438.0839	0.938139707	71
79				33.22	0		
80	1.6	235	233.9	13.59	4044.628	0.999604414	5
81	71	228.4	228.6	28.06895	1860.142	0.961830876	67

According to table (5.5); line 45 (from BANAT to Omdurman) is having the highest CPI value (**0.999925778**) so ranked first. Table (5.5) provides optimal solution for optimal placement of TCSC in line 45 (rank 1) under contingency condition.

5.5.1 Violation in Transmission Lines when line 79 out

The transmission line overloading violations when line 79 taken out has been illustrated in table (5.6) and figure (5.5) as shown bellow.

Table (5.7): Comparison of lines overloading violations when Line79 out

Line NO	Line Loading witout TCSC	Line Loading with TCSC
22	99.05%	99.29%
45	141.67%	6.80%
6	100.39%	100.40%
65	100.03%	99.40%
66	91.40%	91.33%

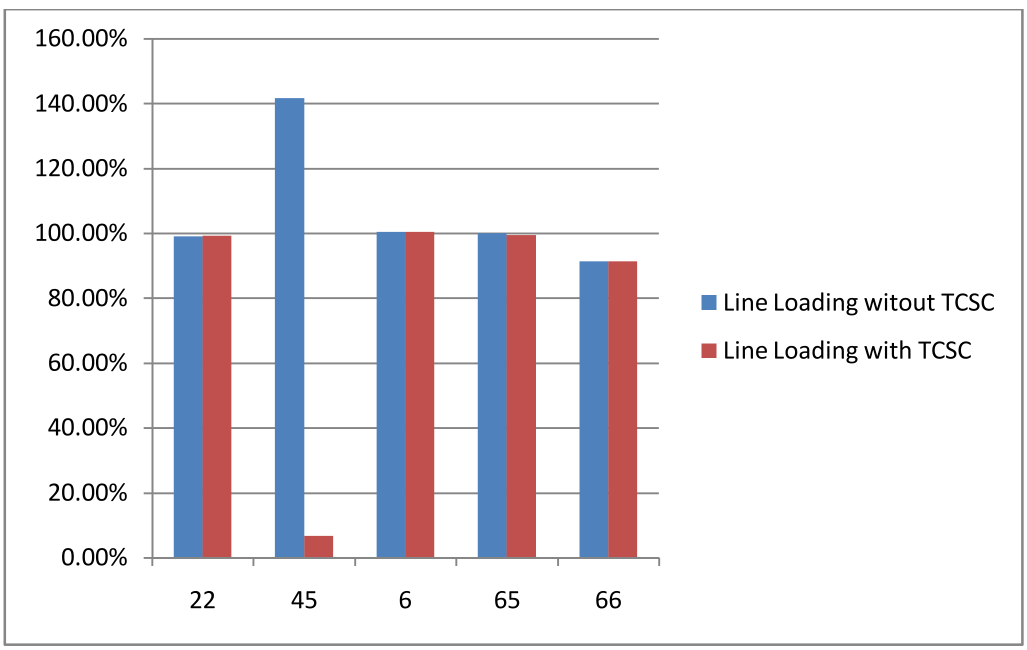

Figure (5.5): Comparison of lines overloading violations when Line79 out

From the above table (5.6) and figure (5.5) it is observed that with optimal location of TCSC in line 45 (from BANAT to Omdurman) decrease the overloading from 141% to 6.8% through distributing the loading to other lines.

5.5.2 Violation in Transmission Lines when line 20 out

The transmission line overloading violations when line 20 taken out has been illustrated in table (5.7) and figure (5.6) as shown bellow.

Table (5.8): Comparison of lines overloading violations when Line 20 out

Line NO	Line Loading without TCSC	Line Loading with TCSC
22	102.55%	103.38%
42	80.49%	80.02%
45	390.23%	21.90%
6	99.89%	99.84%
67	82.18%	82.94%

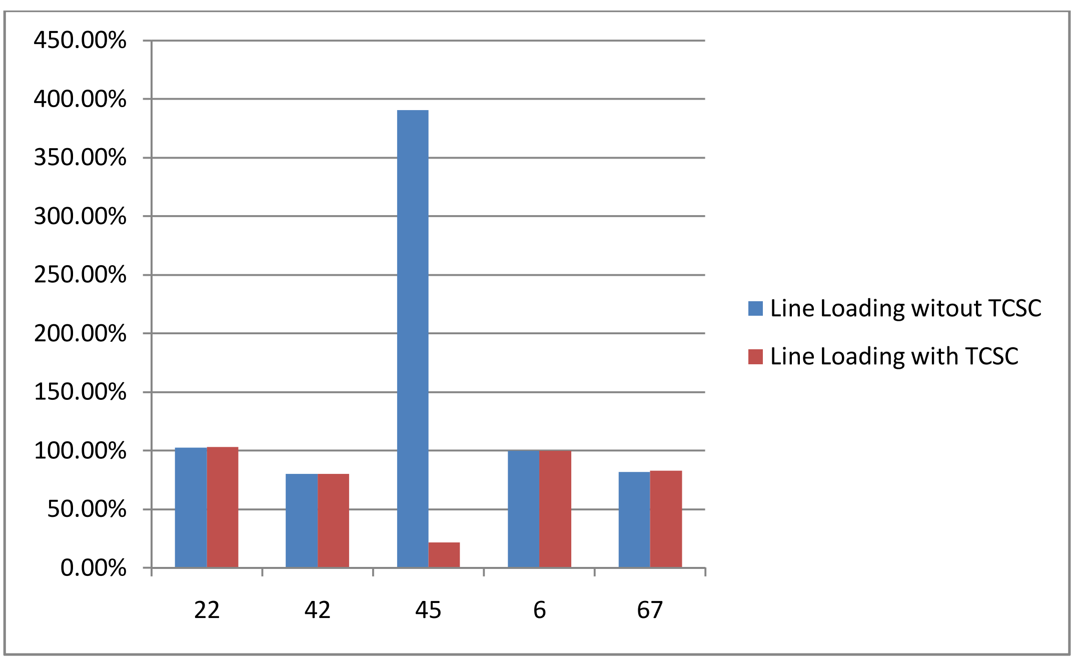

Figure (5.6): Comparison of lines overloading violations when Line 20 out

From the above table (5.7) and figure (5.6) it is observed that with optimal location of TCSC in line 45 (from BANAT to Omdurman) decrease the overloading from 390.23% to 21.9% through distributing the loading to other lines.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

As per the objective study of the thesis, the simulation result shows that the effective placement of FACTS device TCSC in optimal location of the transmission line based on performance indices decreases the overloading of line under Normal operating condition and contingency condition. The TCSC changes the real and reactive power of the system in any location, but the optimal location presents the best benefit on power losses. Also system damping was improved when TCSC connected in its optimal location.

6.2 Recommendations

The following suggested for future studies in this field:

i. Employ of Genetic Algorithm (GA) in tuning of TCSC parameters.
ii. Employ of Power Oscillation Damper (POD) in order to enhance dynamic and transient stability.
iii. Introduce another FACTS device such as SVC in order to enhance voltage profile.
iv. Perform transient stability analysis to check the improvement of system dynamic stability due to TCSC implementation in Sudanese national grid.

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APPENDICES

Appendix A: PSO Code

```
%--=====-=====---Particle Swarm Optimization algorithm:------=====-------
%----===========================================================---------
%This procedure is used for optimal tuning (or placement)
%of Power System Stabilizers (PSS) in a multi-machine power system.
%For solving this problem two platforms are employed and linked together
%in a genuine automatic data exchange procedure: Matlab(Mathworks) and
%DIgSILENT (PowerFactory).
%-Matlab    - easy to learn, write and debug;
%-DIgSILENT - acurat power system and controller modeling;
%           - Modal analysis module
%----===========================================================---------
%----===========================================================---------
%Variable initialization
clear; clc; %Clear the workspace and the command window
nr_particle=20;   %Number of particle
nr_gen=20;        %Number of iterations
particle_size=20;%Particle size
nr_PSS=4;
%Lower and upper eigenvalue filter bounds
above_hz=0.1;    %Lower hz filter
under_hz=7;      %Upper hz filter
%END Lower and upper eigenvalue filter bounds
c1=0.6; c2=0.3; alfa=10; beta=1; gama=1; %Multi-objective function
constants
teta_0=-2.5; epsilon_0=0.6; %Wedge-shape boundries
%----============----Particle's definition domain====--------------=====
%----===========================================================---------
Klow=0.1; Khigh=50; Tlow=0.01; Thigh=3;
%----===========================================================---------
%----===========================================================---------
%Construct and/or fill the communication .csv files between Matlab and
DIgsilent
csvwrite('index.csv', []); csvwrite('Eigen.csv', []);
csvwrite('Eigen2.csv', []);
csvwrite('Eigen3.csv', []); csvwrite('Eigen4.csv',
[]);csvwrite('Switch.csv', []);
csvwrite('gen_act.csv', []); csvwrite('Particle.csv', []);
csvwrite('Particle2.csv', []);
csvwrite('Particle3.csv', []); csvwrite('Particle4.csv', []);
csvwrite('Switch.csv', 1);
csvwrite('nr_particle.csv', nr_particle); csvwrite('nr_gen.csv', nr_gen);
csvwrite('index.csv', 1); csvwrite('gen_act.csv', 1);
[Switch] = textread('Switch.csv'); %Read the state of the Switch
%END Construct and/or fill the communication .csv files between Matlab and
DIgsilent
%Variable initialization
Fobj_caz1=0;
best_Fobj_ever=0;
swich=[]; particle_pt_validare=[]; vector=[]; index=1;
nr_invalid_particle=0; evolutie=[]; Fobj=[]; vect_best_Fobj_ever=[];
vect_best_particle_ever=[]; best_Fobj_ever=[]; best_particle_ever=[];
v=rand(nr_particle,particle_size); %Initialize particle's random speeds
%END Variable initialization
[v]=viteze(v); %Generate negative and pozitive speeds
```

```
%Construct the population of particles
[original_pop]=Population(nr_particle, nr_PSS, Klow, Khigh, Tlow, Thigh);
%Generate population of particle
%load original_pop original_pop %Load a predefine population of particles
%END Construct the population of particles
tic %Start the watch
%Start the iterative process
for gen_act=1:nr_gen
    vect_Fobj_pop=[]; %Variable initialization
    w1=0.8-((0.8-0.2)*gen_act)/nr_gen; %Weighting function of the multi-
objective function
    while index<=nr_particle %Begin the data exchange between Matlab-
DigSILENT for every particle of each generation
          [Switch] = textread('Switch.csv');  %Read the switch file

          particle1=original_pop(index,1:5);           %Take every particle
          particle_invers1=particle1';                 %Rewrite particle as
collumn
          csvwrite('Particle.csv', particle_invers1); %Write Particle.csv
file with the 'index-th' particle

          particle2=original_pop(index,6:10);           %Take every
particle
          particle_invers2=particle2';                 %Rewrite particle as
collumn
          csvwrite('Particle2.csv', particle_invers2);

          particle3=original_pop(index,11:15);           %Take every
particle
          particle_invers3=particle3';                 %Rewrite particle as
collumn
          csvwrite('Particle3.csv', particle_invers3);

          particle4=original_pop(index,16:20);           %Take every
particle
          particle_invers4=particle4';                 %Rewrite particle as
collumn
          csvwrite('Particle4.csv', particle_invers4);

          load Particle.csv;
          load Particle2.csv;
          load Particle3.csv;
          load Particle4.csv;

          csvwrite('Switch.csv',1); %Rewrite the Switch.csv file for
DigSILENT to start doing its computation
          load Switch.csv;
          while Switch==1 %The loop which makes Matlab to wait DigSILENT to
compute
                for o=1:4000 %The loop for delaying the switch scan
                    %Optimal_Solution=[best_Fobj_ever best_particle_ever]
                %Fobj_caz1
                best_Fobj_ever
                end
                [Switch] = load('Switch.csv'); %Read the Switch.csv file
                if Switch==0 %The condition of breaking out from while loop
                   break
                end
```

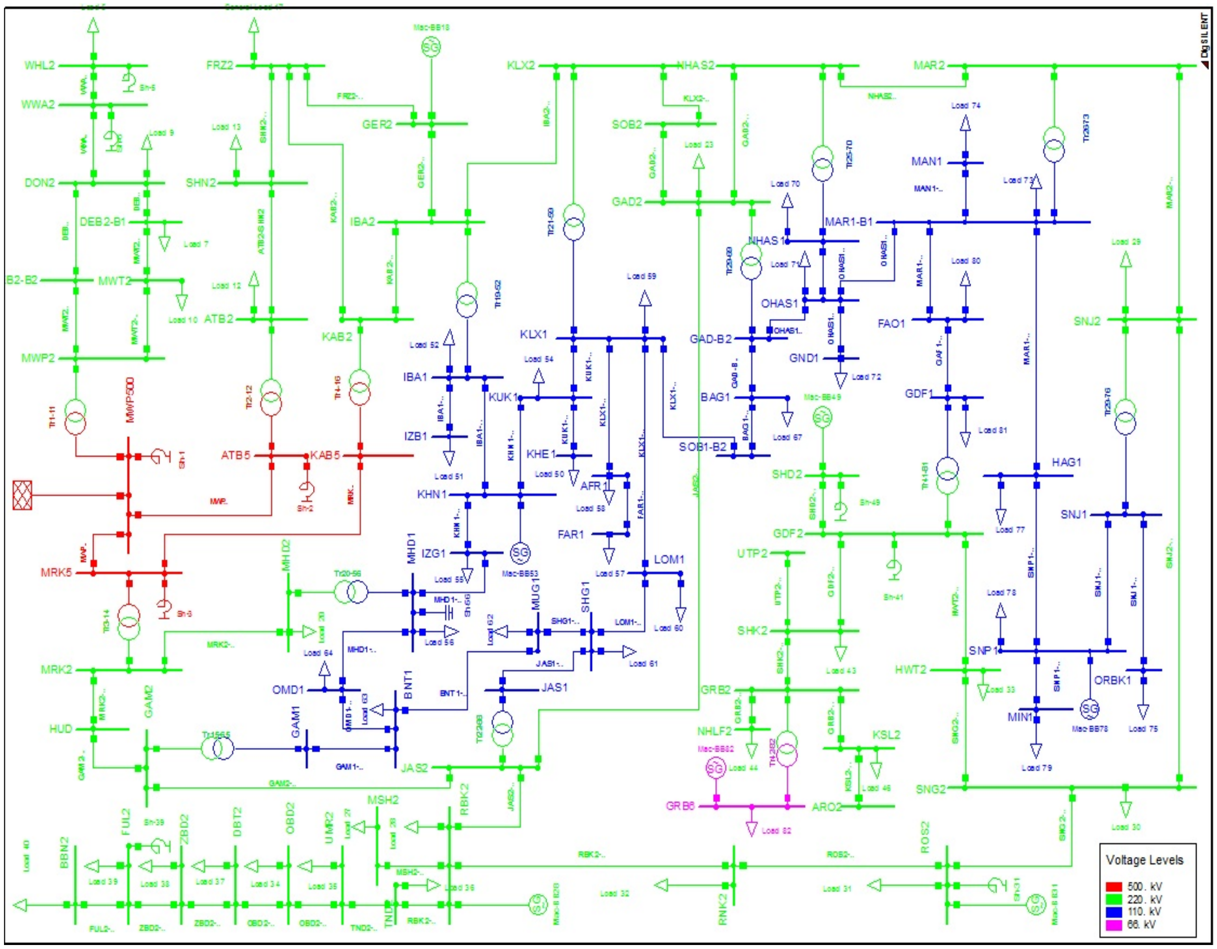
```
          end
          load Eigen.csv; %Read the system eigenvalues from Eigen.csv file
          load Eigen2.csv;
          load Eigen3.csv;
          load Eigen4.csv;
%Particle's validation sequence
          swich=0;
          [d,s]=size(Eigen);
          real_particle=[];
          real_particle1=[];
real_eig_caz1=Eigen(:,1);
complex_eig_caz1=Eigen(:,2);
z=find(real_eig_caz1>0);
[x1,y]=size(z);

particle_pt_validare=[];
if x1>0
      index=index-1;
      particle_pt_validare=[];
      %Define the PSS gain and time constants within the definition domain
      for i=1:nr_PSS
      K=Klow+(Khigh-Klow)*rand(1);
      T1=Tlow+(Thigh-Tlow)*rand(1);
      T2=Tlow+(Thigh-Tlow)*rand(1);
      T3=Tlow+(Thigh-Tlow)*rand(1);
      T4=Tlow+(Thigh-Tlow)*rand(1);
      particle_pt_validare=[particle_pt_validare K, T1, T2, T3, T4]; %The
new particle for validation
      end

      %END Define the PSS gain or time constant within the definition
domain

      original_pop(index+1,:)=particle_pt_validare; %Replace the invalid
particle from the population with a new particle
      swich=1;
       nr_invalid_particle=nr_invalid_particle+1;
    end
%END Particle's validation sequence
          if swich==0
%--------------------------------------------------
%Filter only the positive complex eigenvalues
ind_caz1=find(Eigen(:,2)>0);
Eigen=Eigen(ind_caz1, :);
%END Filter only the positive complex eigenvalues

%Damping ratio
[size_caz1, r]=size(Eigen);
damp_caz1=[];
for i=1:size_caz1
    damp_caz1_var=-Eigen(i, 1)/(sqrt(Eigen(i,1).^2 + Eigen(i,2).^2));
    damp_caz1=[damp_caz1; damp_caz1_var];
end
%END Damping ratio

%Filter the oscillation modes which are too damped
ind=find(damp_caz1 > 0.7);
damp_caz1(ind)=[];
```

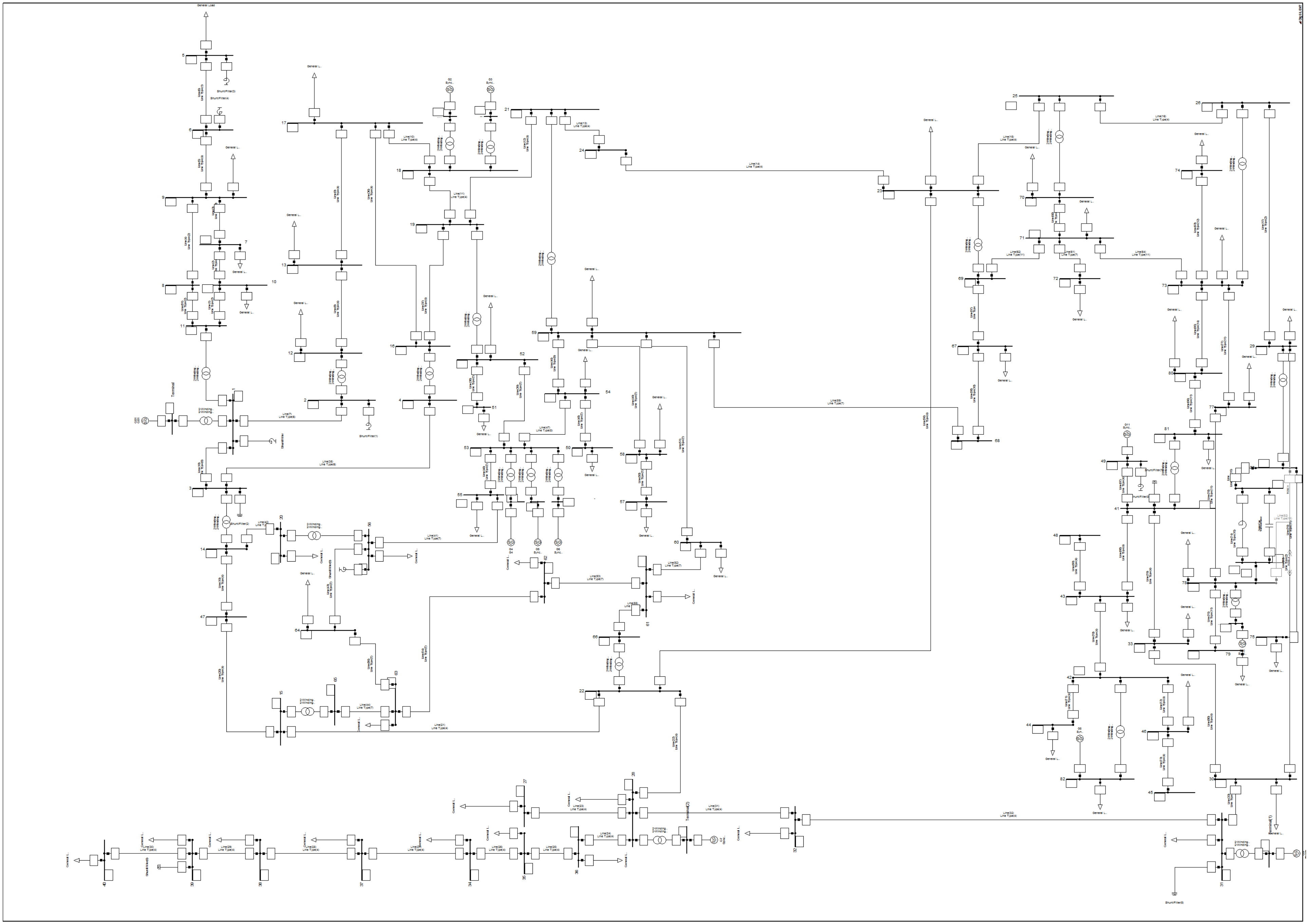
```
Eigen(ind, :)=[];
%END Filter the oscillation modes which are too damped

% Filter the eigenvalues between above_hz and under_hz
 hz_eigen_caz1=abs(Eigen(:, 2))/(2*pi); %Frequency of oscillation
 index_oscil_min_caz1=find(hz_eigen_caz1 > above_hz); %Index of the
oscillatory mode which are above 'above_hz' Hz
 Eigen=Eigen(index_oscil_min_caz1, :);
 damp_caz1=damp_caz1(index_oscil_min_caz1, :); %The vector with eigenvalues
damping factors
 hz_eigen_caz1=hz_eigen_caz1(index_oscil_min_caz1, :);   %The vector with
the frequency of the eigenvalues
 index_oscil_max_caz1=find(hz_eigen_caz1 < under_hz); %Index of the
oscillatory mode which are below 'under_hz' Hz
 Eigen=Eigen(index_oscil_max_caz1, :);
 damp_caz1=damp_caz1(index_oscil_max_caz1, :); %The vector with eigenvalues
damping factors
 hz_eigen_caz1=hz_eigen_caz1(index_oscil_max_caz1, :);   %The vector with
the frequency of the eigenvalues
%END Filter the eigenvalues between above_hz and under_hz

%Filter the electromechanical oscillations of interest
%-------------------------------------------------------
index_teta_caz1=find(Eigen(:,1) > teta_0);
Eigen=Eigen(index_teta_caz1,:);
damp_caz1=damp_caz1(index_teta_caz1);
% index_epsilon_caz1=find(damp_caz1 < epsilon_0);
% damp_caz1=damp_caz1(index_epsilon_caz1);
% Eigen=Eigen(index_epsilon_caz1,:);
%-------------------old-------------------------

%-------------------------------------------------------

[r,t]=size(Eigen);
%-----------------new2-----------------------------

%END Filter the electromechanical oscillations of interest
%Objective function
Fobj_caz1=[];
[x,y]=size(Eigen);

for i=1:x
    first=(teta_0-Eigen(i, 1))^2;
    second=(epsilon_0-damp_caz1(i, 1))^2;
    Fobj_caz1_var=beta*first + alfa*second*gama;
    Fobj_caz1=[Fobj_caz1; Fobj_caz1_var];
end
Fobj_caz1=sum(Fobj_caz1);
Fobj=Fobj_caz1;

 vect_Fobj_pop=[vect_Fobj_pop; Fobj]; %Vector of the obj function from
generation 'x'
%END Filter the electromechanical oscillations of interest
%%%%END Electromechanical Oscillations filter%%%
          end
         load Particle.csv;
         index=index+1; %Pass to next particle
```

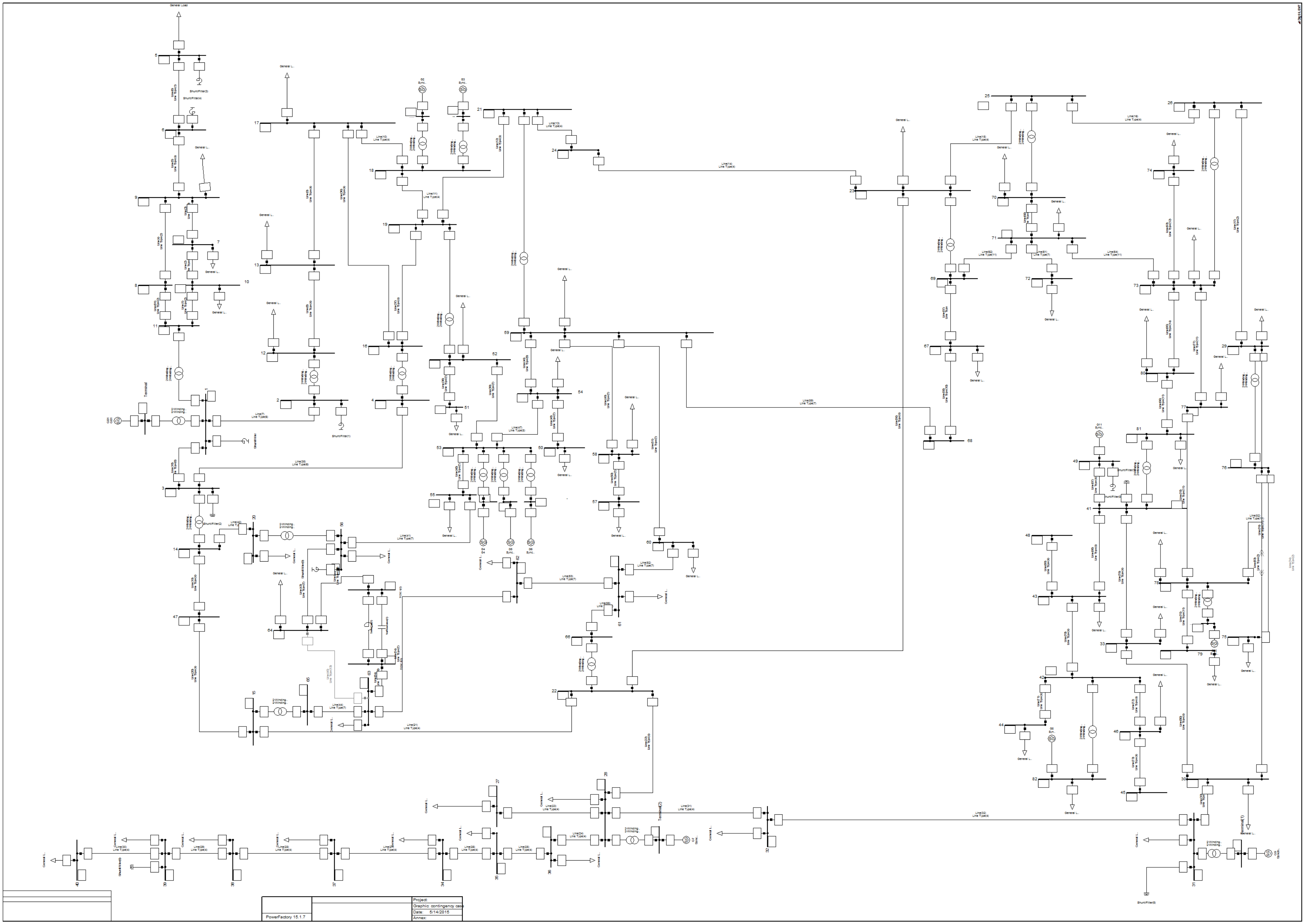
```
        csvwrite('index.csv', index); %Increment the index
    end
    index_best_Fobj_pop=find(vect_Fobj_pop==min(vect_Fobj_pop)); %Index of
the best obj. function from the population
    best_Fobj_pop=vect_Fobj_pop(index_best_Fobj_pop); %Best objective
function from generation 'x'
    best_particle_pop=original_pop(index_best_Fobj_pop, :); %Best particle
from generation 'x'
    vect_best_Fobj_ever=[vect_best_Fobj_ever; best_Fobj_pop]; %Vector of
best obj function ever
    vect_best_particle_ever=[vect_best_particle_ever;
best_particle_pop];%Vector of best particle ever


index_best_Fobj_ever=find(vect_best_Fobj_ever==min(vect_best_Fobj_ever));
%Index of the best obj. function ever
    index_best_Fobj_ever=index_best_Fobj_ever(1);
    best_Fobj_ever=vect_best_Fobj_ever(index_best_Fobj_ever);%Best fobj
ever

best_particle_ever=vect_best_particle_ever(index_best_Fobj_ever,:);%Best
particle ever
    best_particle_eever=best_particle_ever'; %Written as collumn

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if gen_act==1
       pbest=original_pop;
    end
%Elitism
    if gen_act>=2
       [original_pop, vect_Fobj_pop]=Elitism(original_pop, vect_Fobj_pop,
best_Fobj_ever, best_particle_ever);
    end
%END Elitism
    evolutie = [evolutie best_Fobj_ever]; %The objective function evolution
    [ki,ou]=size(original_pop);
    pop=[]; vit=[];
%Swarm and speed actualization according to the particle pozition
    if gen_act>=2
       for kk=1:ki
           if vect_Fobj_pop(kk,1) > past_vect_Fobj_pop(kk,1);
              pbest(kk, :)=past_original_pop(kk, :);
              v(kk, 1)=past_v(kk, 1);
           end
       end
    end
%END swarm and speed actualization according to the particle pozition
    for ll=1:ki
        particle=original_pop(ll, :);
        v_crt=v(ll,:);
        w2=c1*rand(1);
        w3=c2*rand(1);
%Particle speed computation
        v_crt=w1*v_crt+w2*(pbest(ll,:)-particle)+w3*(best_particle_ever-
particle);
%END Particle speed computation
        particle=particle+v_crt; %Actualization of the particle pozition
        pop=[pop; particle];
```

```
        vit=[vit; v_crt];
    end
%Prevent particle to go out from it's definition domain
    [cv, bn]=size(pop);

       for ii=1:cv
        for z=0:5:15
        if pop(ii, 1+z) > Khigh
           pop(ii, 1+z) = Khigh;
           else if pop(ii, 1+z) < Klow
                   pop(ii, 1+z) = Klow;
                end
        end

        if pop(ii, 2+z) > Thigh
           pop(ii, 2+z) = Thigh;
           else if pop(ii, 2+z) < Tlow
                   pop(ii, 2+z) = Tlow;
               end
        end
        if pop(ii, 3+z) > Thigh
           pop(ii, 3+z) = Thigh;
           else if pop(ii, 3+z) < Tlow
                   pop(ii, 3+z) = Tlow;
               end
        end
        if pop(ii, 4+z) > Thigh
           pop(ii, 4+z) = Thigh;
           else if pop(ii, 4+z) < Tlow
                   pop(ii, 4+z) = Tlow;
               end
        end
        if pop(ii, 5+z) > Thigh
           pop(ii, 5+z) = Thigh;
           else if pop(ii, 5+z) < Tlow
                   pop(ii, 5+z) = Tlow;
               end
        end
        end
    end
%END Prevent particle to go out from it's definition domain
    %pop=plus;
    [fg, gj]=size(pop);
    past_original_pop=original_pop;
    past_v=v;
    past_vect_Fobj_pop=vect_Fobj_pop;
    original_pop=pop;
    v=vit;
    gen_act=gen_act+1;
    csvwrite('gen_act.csv', gen_act);
    index=1;
    csvwrite('nr_particle.csv', nr_particle);
    csvwrite('Switch.csv', 1);
    save andrei; %Save the data if an unexpected error ocurres
end
%END Start the iterative process
jjj=plot(evolutie) %Plot the optimization proces evolution
toc %Stop watch
```

Appendix B: Sudanese National Grid






Project:
Graphic: contingency case
Date: 5/14/2015
Annex:
PowerFactory 15.1.7

Appendix C: Generators Data

Name	kV	MVA	MW	xd p.u.	xd' p.u.	xd'' p.u.	xq p.u.	xq' p.u.	xq'' p.u.	Td'o s	Td''o s	Tq'o s	Tq''o s
Garri G1 (GAS1)	11	41.3	37.17	0.9	0.26	0.24	0.54	0.3	0.21	1.588889	0.047077	0	0.012833
Garri G2 (GAS2)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G3 (ST01)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G4 (GAS3)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G5 (GAS4)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G6 (ST02)	11	41.3	37.17	0.93	0.302	0.365	0.69	0.3	0.341	2.597849	0.036258	0	0.029652
Garri G7 (GAS5)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G8 (GAS6)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G9 (ST03)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G10 (GAS7)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G11 (GAS8)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G12 (ST04)	11	41.3	37.17	0.953	0.312	0.283	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G13 (ST09)	11	70	60	1.66	0.18	0.132	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Garri G14 (ST10)	11	70	60	1.66	0.18	0.132	0.573	0.3	0.402	2.314628	0.037189	0	0.049812
Jebel Aulia G1	11	41.25	60	0.99	0.318	0.288	0.615	0.3	0.306	1.702424	0.046189	0	0.01642
Merowe G1	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G10	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G2	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G3	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G4	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G5	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G6	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G7	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G8	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Merowe G9	13.8	140	127.3	0.883	0.275	0.18	0.601	0.3	0.213	8.843	0.089	0	0.219
Roseires G1	11	44.5	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07
Roseires G2	11	44.5	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07
Roseires G3	11	44.5	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07
Roseires G4	11	43	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07
Roseires G5	11	43	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07
Roseires G6	11	43	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07

Roseires G7	11	43	40	0.89	0.26	0.21	0.54	0	0.22	4.67	0.05	0	0.07
Sennar G1	11	9.4	7.5	1.02	0.3	0.2	0.65	0.3	0.25	5	0.041	0	0.074
Sennar G2	11	9.4	7.5	1.02	0.3	0.2	0.65	0.3	0.25	5	0.041	0	0.074
Khartoum North G1	11	41.25	30	1.634	0.232	0.17	1.6	0.48	0.16	7.2	0.05	0.9	0.048
Khartoum North G2	11	41.25	30	1.634	0.232	0.17	1.6	0.48	0.16	7.2	0.05	0.9	0.048
Khartoum North G3	11	75	60	2.3	0.23	0.148	2.1	0.55	0.16	7.69	0.04	0.96	0.048
Khartoum North G4	11	75	60	2.3	0.23	0.148	2.1	0.55	0.16	7.69	0.04	0.96	0.048
Khartoum North G5	11	137.5	110	1.97	0.27	0.24	1.9	0.48	0.2	8.2	0.035	0.997	0.035
Khartoum North G6	11	137.5	110	1.97	0.27	0.24	1.9	0.48	0.2	8.2	0.035	0.997	0.035
Khartoum North Gas 1	11	23.5	17	2.16	0.2	0.142	2.1	0.3	0.15	5.34	0.05	0.59	0.05
Khartoum North Gas 3	11	25	17	2.16	0.2	0.142	2.1	0.3	0.15	5.34	0.05	0.59	0.05
Khartoum North Gas 4	11	25	17	2.16	0.2	0.142	2.1	0.3	0.15	5.34	0.05	0.59	0.05
GBA disel GT1	6.6	4.5	2.5	1.85	0.89	0.235	0.89	0.3	0.22	4.8	0.02	0.59	0.08
GBA disel GT2	6.6	3.5	2	1.85	0.89	0.235	0.89	0.3	0.22	4.8	0.02	0.59	0.08
GBA kaplain GT1	6.6	6.6	2	1.138	0.306	0.205	0.683	0.3	0.2	6	0.05	0.59	0.1
GBA kaplain GT2	6.6	6.6	2	1.138	0.306	0.205	0.683	0.3	0.2	6	0.05	0.59	0.1
GBA pump 1	6.6	2.6	2	1.28	0.32	0.25	0.92	0.3	0.315	5.2	0.05	0.59	0.06
GBA pump 2	6.6	2.6	2	1.28	0.32	0.25	0.92	0.3	0.315	5.2	0.05	0.59	0.06
GBA pump 3	6.6	2.6	2	1.28	0.32	0.25	0.92	0.3	0.315	5.2	0.05	0.59	0.06

Appendix D: Transmission Lines Data

from	to	length	no.of circuit	nominal voltage kV	conductor type&size	R1 (Ω/km)	X1 (Ω/km)	C1 (nf/km)	RO (Ω/km)	XO (Ω/km)	CO (nf/km)
kuku	kh.north	4.5	2	110	2*350mm^2ACSR	0.0384	0.302	9.5	0.3995	1.206	6.53
kilox	kuku	14.6	2	110	1*350mm^2ACSR	0.087	0.379	9.5	0.502	1.93	4.3
kilox	faroug	14	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
jebel aulia	shagara	39	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
kuku	kh.east	3.2	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
eid babiker	kh.north	12	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
eid babiker	alaizba	11	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
kh.north	Izergab	12	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
mahadia	Izergab	8	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
mahadia	oumdurman	9.3	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
mugran	banat	3.8	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
banat	omdurman	5.9	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
mugran	shagara	11	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
kilox	local market	3	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
shagara	local market	7.8	2	110	2*240mm^2ACSR	0.067	0.269	13.06	0.262	1.044	5.75
kilox	bagair	28	1	110	1*95mm^2ACSR	0.348	0.421	8.6	0.546	1.38	5.3
giad	bagair	3	1	110	1*95mm^2ACSR	0.348	0.421	8.6	0.546	1.38	5.3
giad	hasa hesa	77	1	110	1*95mm^2ACSR	0.348	0.421	8.6	0.546	1.38	5.3

meringan	**hasa hesa**	55	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
meringan	**hag abdalla**	35	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
sennar hydro	**hag abdalla**	60	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
sennar hydro	mina sharif	69	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
sennar hydro	sennar jun	10	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
sennar jun	rabak	96	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
meringan	**elfau**	71	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
gedarif	**elfau**	153	1	110	1*95mm²ACSR	0.348	0.421	8.6	0.546	1.38	5.3
meringan	**managil**	75.6	1	110	1*150mm²ACSR	0.105	0.289	9.65	0.315	0.867	5.4
gamoeia	banat	16.5	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
hasa hesa	genaid	15	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
kilox1	**giad**	43	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
kilox2	**giad**	43	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
meringan1	**giad**	141	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
meringan2	**giad**	141	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
meringan	**sennar jun**	84	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
sennar jun	**singa**	50	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
singa	**roseires**	178	2	220	1*400mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
garri	**eid babiker**	60	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
kilox	**eid babiker**	14	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75

free zone	shendi	115	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
atbara	shendi	140	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
atbara	barber	38	4	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
barber	algobosh	25	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.18	5.75
barber	alsherek	121	4	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.19	5.75
alsherek	dagash	89	4	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.20	5.75
dagash	abuhamad	30	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.21	5.75
abuhamad	mugrat	20	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.22	5.75
jebel aulia	**giad**	36	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
jebel aulia	**gamoeia**	37	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
markhiat	**mahdia**	21	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
markhiat	**gamoeia**	37	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
garri	**free zone**	5	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
kabbashi	**free zone**	34	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
kabbashi	eid babiker	30	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
mushkur	**jebel aulia**	100	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
mushkur	rabak	100	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
rank	**roseires**	172.8	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
rabak	rank	163.3	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
rabak	kosti	27	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
kosti	tandalti	84	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
tandalti	umrawaba	78.3	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75

rabak	umrawaba	154.9	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
umrawaba	elrahad	70	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
elrahad	obeid	60	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
obeid	aldebebat	92	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.18	5.75
aldebebat	abuzabad	66	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.19	5.75
abuzabad	alfula	120	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.20	5.75
alfula	babanosa	80	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.21	5.75
aldebebat	aldalang	58	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.22	5.75
umrawaba	abasia-tagali	84	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.23	5.75
abasia-tagali	rashad	42	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.24	5.75
rashad	abugibeha	48	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.25	5.75
abugibeha	kalogy	75	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.26	5.75
kalogy	talody	69	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.27	5.75
talody	kadogly	81	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.28	5.75
kadogly	lagawa	80	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.29	5.75
lagawa	alfula	92	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.30	5.75
singa	hawata	90	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
gedarif	gle alnahl	49.6	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
gle alnahl	hawata	48.9	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
hawata	eldender	44.5	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
eldender	senga	42.9	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
gedarif	showak	75.12	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75

showak	girba	62.54	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
girba	kassala	74.5	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
girba	new halfa	48.87	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
kassala	aroma	43.78	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
merowe	merowe town	34.55	2	220	1*480mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
debba	merowe town	139.3	2	220	1*480mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
debba	dongola	139.38	2	220	1*480mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
dongola	wawa	166	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
wawa	old halfa	205	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
atbara	port sudan	448.92	1	220	1*480mm²ACSR	0.076	0.403	9.02	0.551	2.159	4.4
port sudan	Arkiaey	75	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
port sudan	port sudan ring	30			2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
merowe	**markhiat**	346	2	500	4*325mm²ACSR	0.028	0.276	13.083	0.3445	0.981	9.99
kabbashi	**markhiat**	36.8	1	500	4*325mm²ACSR	0.028	0.276	13.083	0.3445	0.981	9.99
merowe	atbara	236.7	1	500	4*325mm²ACSR	0.028	0.276	13.083	0.3445	0.981	9.99
gedarif	rawesda	38	1	66	1*95mm²ACSR	0.348	0.397	8.96	0.47	1.45	5.7
showak	rawesda	32	1	66	1*95mm²ACSR	0.348	0.397	8.96	0.47	1.45	5.7
showak	elgriba	70	1	66	1*95mm²ACSR	0.348	0.397	8.96	0.47	1.45	5.7
kassala	elgriba	85	1	66	1*120mm²ACSR	0.255	0.386	9.6	0.44	1.45	5.7
kilo3	elgriba PP	3	1	66	1*120mm²ACSR	0.255	0.386	9.6	0.44	1.45	5.7
elgriba 220	halfa	52	1	66	1*120mm²ACSR	0.255	0.386	9.6	0.44	1.45	5.7
kilo3	**elgriba 220**	3	1	66	1*120mm²ACSR	0.255	0.386	9.6	0.44	1.45	5.7

Rosaries	KarnKarn	80	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
KarnKarn	kurmuk	50	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
Rosaries	Umdafra	55	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
KarnKarn	BAO	39	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
KarnKarn	Geisan	25	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
Babanusa	Adila	90	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Adila	El Da'ein	100	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.18	5.75
El Da'ein	Nyala	180	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.19	5.75
Nyala	El Fashir	200	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.20	5.75
Nyala	Kass	95	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Kass	Zalinge	110	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.18	5.75
Zalinge	Genena	132	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.18	5.75
EL Fasher	Um Kadadh	145	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
Zalinge	Garsila	80	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75
Abu Zabad	Al Nuhood	94	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Al Nuhood	Gibesh	116	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Sodari	Hamarat AL Sheik	126	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
AL Obeid	Bara	63	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Bara	Sodari	167	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Sodari	Hamarat Al Wiz	132	2	220	2*240mm²ACSR	0.067	0.302	13.06	0.262	1.2/1.17	5.75
Kalogi	Heban	60	2	110	2*240mm²ACSR	0.067	0.269	13.06	0.262	1.044	5.75