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# Determining the Optimal Placement of TCSC for Congestion Management in South East Nigerian 11-Bus Network

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**ABSTRACT**

In a deregulated electricity industry, congestion is most likely to occur and FACTS devices have been proven to be very effective in mitigating this challenge. In this paper a sensitivity based analysis is used to determine the optimal place to locate series FACTS devices, the device used for the investigation is Thyristor Controlled Series Capacitor (TCSC). This approach was tested on the South East Nigerian 11 – bus network. The Power System Analysis Toolbox (PSAT), was used for the simulation of the system. The load flow results obtained showed the effectiveness of the method.



## Introduction

The ongoing expansion and growth of the electric utility industry and deregulation in most nations have lead to the transmission systems being stressed closer to its thermal and stability limit. In a deregulated power system, congestion is most likely to occur because the market for buying and selling of energy is being operated without the constraints of the power system being taken care of. The traditional method of building new transmission lines and infrastructure to mitigate the congestion problem has proven to be more expensive, difficult and time consuming.

Researchers are relentlessly trying to find improved technique to enable full utilization of the existing transmission infrastructure in order to optimize reliability and profitability of the transmission system.

This topic is considered very important to both the developed and developing countries like Nigeria because it addresses the problem of energy losses. Since flexible alternating current transmission system (FACTS) have good impact on load flows, it can be effective in mitigating reactive power losses in transmission systems. This invariably, will optimize the use of power transmission facilities.

Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC Transmission Systems (FACTS). FACTS devices by controlling the power flows in the network without generation rescheduling or topological changes can improve the performance of a power system considerably. The insertion of such devices in electrical systems seems to be a promising strategy to decrease the transmission congestion and to increase available transfer capability. Firstly, the recent development in high power electronics has made these devices cost effective and secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost effective means of dispatching specified power transactions. It is important to ascertain the location for placement of these devices because of their considerable costs [2].

### Flexible Ac Transmission System (Facts)

The FACTS is a generic term representing the application of power electronics based solutions to AC power system. These systems can provide compensation in series or shunt or a combination of both series and shunt. The FACTS can attempt the compensation by modifying impedance, voltage or phase angle. FACTS devices can be connected to a transmission line in various ways, such as in series with the power system (series compensation), in shunt with the power system (shunt compensation), or both in series and shunt.[1]

### Series Facts Devices

The series Compensator could be variable impedance, such as capacitor, reactor, etc. or a power electronics based variable source of main frequency to serve the desired need. Various Series connected FACTS devices are;

- Static Synchronous Series Compensator (SSSC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor Switched Series Capacitor (TSSC)
- Thyristor Controlled Series Reactor (TCSR)
- Thyristor Switched Series Reactor (TSSR)

### Shunt Facts Devices

Shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Various shunt connected controllers are;

- Static Synchronous Series Compensator (STATCOM)
- Static VAR Compensator (SVC)
- Thyristor Controlled Reactor (TCR)
- Thyristor Switched Capacitor (TCS)

### Combined Series-Shunt Facts Devices

This may be a combination of separate shunt and series controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements.

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In principle, combined shunt and series controllers inject current into the system with shunt part of controller and voltage with the series part of controller. Various combined series shunt Controllers are: Various combined series shunt Controllers are [1].

- Unified Power Flow Controller
- Thyristor Controlled Phase Shifter

**Thyristor Controlled Series Capacitor (Tcsc)**

The IEEE defines the TCSC as a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smooth variable series capacitive reactance. Series capacitive compensation works by reducing the effective series impedance of the transmission line by cancelling part of the inductive reactance. A basic set up of a TCSC is shown in Figure1.

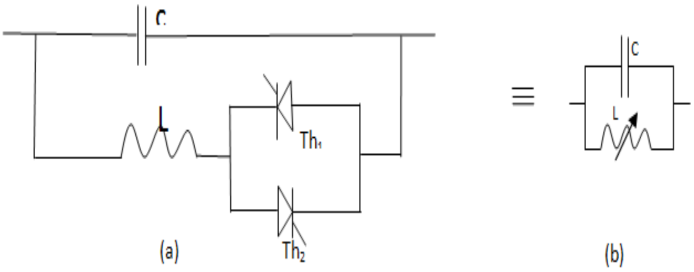


**Fig 1. TCSC configuration (a) Basic circuit (b) The equivalent circuit**

In most cases, several TCSC devices are connected in series to improve the capacity and therefore, the performance. One of the functions of TCSC is to provide variable capacitance that will continuously try to balance out the inductive effect of the circuit. On its own part, the TCR at the fundamental system frequency is acontinuously variable reactive impedance, controllable by delay angle α, the steady-state impedance of the TCSC is that of a parallel LC circuit shown in Fig.1 with variable inductance and fixed capacitance. If the capacitive reactance is , $X_c$, and the variable inductance is $X_L(\alpha)$, then,

$$X_{TCSC}(\propto) = \frac{X_C X_L(\propto)}{X_L(\propto) - X_C} \quad (1)$$

Where, $$X_L(\propto) = \frac{X_L}{\pi - 2\alpha - Sin\alpha}\pi \quad (2)$$

α is the firing angle, $X_L = \omega L$, the reactance of the inductor and $X_L(\alpha)$ is the effective reactance of the inductor at firing angle α and is limited thus

$$X_L \leq X_L(\propto) \leq \infty$$

The TCSC impedance becomes a variable parallel LC circuit to the line current which is a constant alternating current source. As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (infinity) towards its minimum $X_L$, the TCSC increases its capacitive impedance, $X_{TCSC,min} = {}^{1}/_{2\pi FC}$, $ie, {}^{1}/_{\omega C}$ until parallel resonance at $X_c = X_L(\alpha)$ is attained and $X_{TCSC,max}$ becomes infinite. Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $X_L X_C / (X_L - X_C)$ at α = 0, where the capacitor is in effect bypassed by the TCR. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor $X_L$, is smaller than that of the capacitor, $X_c$, the TCSC has two operating ranges around its internal circuit resonance: one is the $\alpha_{clim} \leq \alpha \leq \pi/2$ range, where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range, where $X_{TCSC}(\alpha)$ is inductive, as illustrated in Figure2

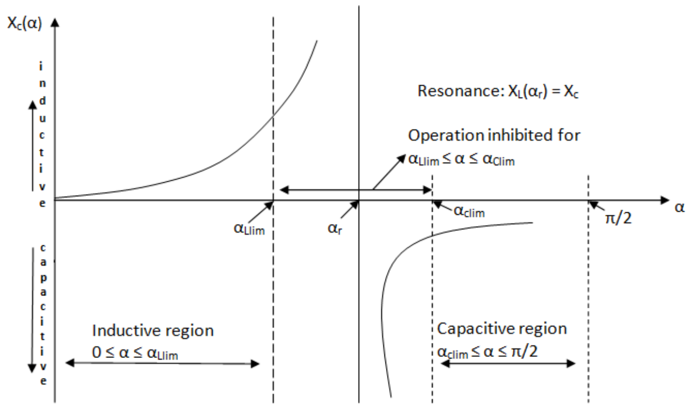


**Figure 2. The Impedance vs. Delay angle α characteristic of the TCSC**

**Optimal Location of TCSC**

**Total system reactive power loss sensitivity**

Here we look at a method based on the sensitivity of the total system reactive power loss with respect to the control variable of TCSC. For TCSC placed between buses i and j, we consider net line series reactance as a control parameter. Loss sensitivity based on control parameter of TCSC placed between buses i and j can be written as.

$$a_{ij} = \frac{\partial Q_L}{\partial x_{ij}} = \left[V_i^2 + V_j^2 - 2V_iV_j cos\delta_{ij}\right]\frac{r_{ij}^2 - x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} \quad (3)$$

Where $\delta_{ij} = \delta_i - \delta_j$

**Criteria for optimal location**

1. In reactive power loss reduction method ($a_{ij}$), TCSC should be placed in a line having the most positive loss sensitivity index.
2. In real power flow performance sensitivity indices ($b_{ij}$) method, TCSC should be placed in a line having most negative sensitivity index.

**Materials and Methods**

Power System Analysis Toolbox (PSAT), a Matlab and GNU/Octave software fully based on Newton Raphson method was used to simulate the steady state model of the South Eastern Nigeria 11-bus power system. The 11 bus network of the South Eastern network in Nigeria was modelled in PSAT-GUI mode and simulated. The network has a total number of 11 buses (6 generator buses and 11 load buses).

**Modelling of Facts Device (TCSC)**

Although FACTS controllers are utilized in the system to perform their primary task of stability control, they also improve the steady state performance of the system. The thesis only considered their impact on the congestion management, formulated as a steady state problem. A static Power Injection Model (PIM) of the TCSC has been used. The injection model represents the TCSC as a device that injects certain amount of active and reactive power into a node.

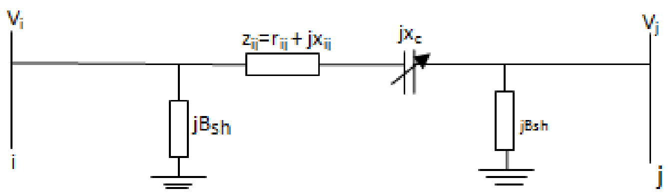


**Figure 3. Static model of line with TCSC**

Fig.3 shows a model of transmission line with TCSC connected between buses i and j. The transmission line is represented by its lumped $\pi$-equivalent parameters, connected between the two buses. During steady state, the TCSC can be considered as a static reactance $-jx_c$. The controllable reactance

$x_c$ is directly used as the control variable in the power flow equations. The corresponding power injection model of TCSC, incorporated in the transmission line, is shown in Fig.4 The real ($P_i^F$) and reactive ($Q_i^F$) power injections, due to TCSC at buses i and j are given by the following equations.

$$P_i^F = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} cos\delta_{ij} + \Delta B_{ij} sin\delta_{ij}) \quad (5)$$

$$Q_i^F = -V_i^2 \Delta B_{ij} - V_i V_j (\Delta G_{ij} sin\delta_{ij} - \Delta B_{ij} cos\delta_{ij}) \quad (6)$$

$$P_j^F = V_j^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} cos\delta_{ij} + \Delta B_{ij} sin\delta_{ij}) \quad (7)$$

$$Q_j^F = -V_j^2 \Delta B_{ij} + V_i V_j (\Delta G_{ij} sin\delta_{ij} + \Delta B_{ij} cos\delta_{ij}) \quad (8)$$

Where,

$$\Delta G_{ij} = \frac{x_c r_{ij}(x_i - x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \quad (9)$$

$$\Delta B_{ij} = \frac{-x_c(r_{ij}^2 - x_{ij}^2{}_i + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \quad (10)$$

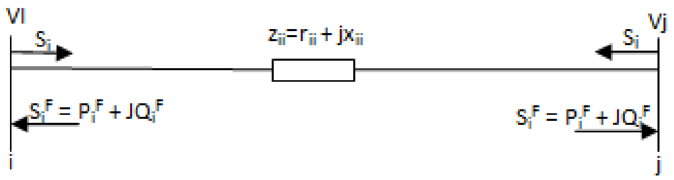


**Figure 4. Static power injection model of TCSC**

where, $V_i$, $V_j$ and $\delta_i$, $\delta_j$ are voltage and angle at buses i and j, respectively. $G_{ij}$ and $B_{ij}$ are the conductance and susceptance of the line-ij.

**Case Study on 11 Bus In South East 330kv Network**

For validation of the proposed method, the steady state model of FACTS device, TCSC, was tested on the South East Nigerian 11-bus, 330kv network. The South East Nigerian network consisting of 11 buses, made up of 5 generator buses and 6 transmission lines buses was simulated using Power System Analysis tool box (PSAT). The system is based on Newton Raphson method. In the analysis, the system was initially simulated without FACTS device and the power flow values recorded were used to place TCSC on the most congested line having the highest power flow. The sensitivity index was calculated using Matlab by applying the total system reactive power loss sensitivity approach. The system with the most positive index was selected for FACTS placement and the system simulated with the device optimally placed for comparison. The system performance was checked for congestion management, power losses reduction and voltage profile stability and found improved.

FIGURE 5 PSAT SIMULATION OF SOUTH EAST NIGERIAN 11 BUS NETWORK WITHOUT FACTS DEVICE

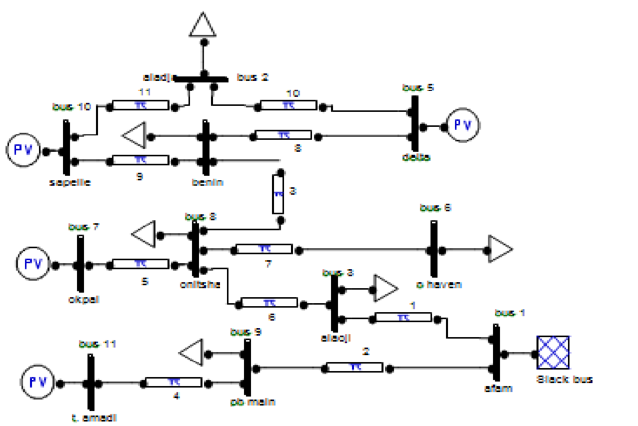


**Fig 5. Base case simulation of 11bus, 330kV South East Nigerian network (without any insertion**

TOTAL LOSSES – WITHOUT FACTS DEVICE
REAL POWER [p.u.] 2.1252
REACTIVE POWER [p.u.] -29.3978

**Optimal Placement Of Facts Device**

Many methods are available for determining the optimal placement of FACTS devices in both vertically integrated and unbundled power systems. Some of them are Sensitivity methods, L-index method, Reactive power spot price index method and some other artificial Intelligence methods like Particle Swarm Optimization (PSO), Fuzzy method, Genetic Algorithm (GA), etc.

Sensitivity method for determining optimal location of TCSC has been suggested in this paper. The approach is based on the sensitivity of the reduction of total system reactive power losses. The sensitivity index are calculated in appendix 1 using Matlab software and shown in Table 2. The values obtained from the sensitivity analysis are used in determining the optimal location of the TCSC.

From the sensitivity index table in Table 4.3 above, as calculated in appendix 1, it is easily observed that line 8-3 (Onitsha – Alaoji) has the most positive sensitivity index value and is thereby considered as the best location for the FACTS device as calculated using the reactive

FIGURE 6 - PSAT SIMULATION OF SOUTH EASTERN NIGERIA NETWORK WITH TCSC PLACED OPTIMALLY

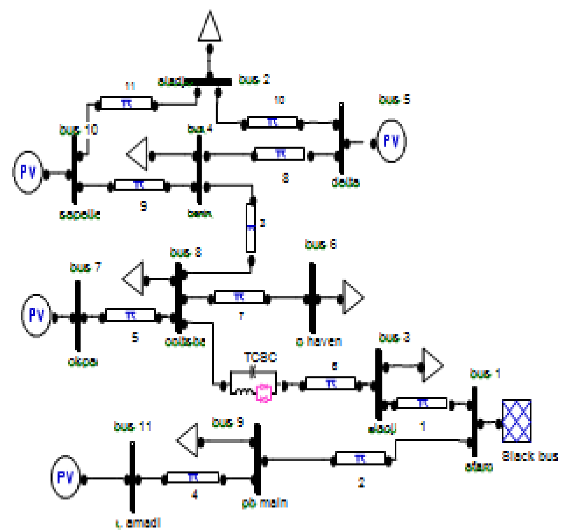


**Fig 6. Simulation of 11bus, 330kV South East Nigerian network with TCSC inserted optimally**

TOTAL LOSSES – WITH FACTS DEVICE OPTIMALLY PLACED
REAL POWER [p.u.] 0.9756
REACTIVE POWER [p.u.] -32.811

**Result and Discussions**

It was observed that for the network without FACTS devices, the real power flow was 14.8384 and the reactive power was 1.8667 forthe line Onitsha – Alaoji. There was a remarkable reduction in power flow when FACTS device (TCSC) was optimally placed. The power reduced to 14.8371 and 1.6323 for active and reactive power respectively, thereby alleviating congestion. The power losses for the line reduced from 1.2787 for active power loss and 6.9329 for reactive power loss to 0 for active power loss and 3.469 for reactive power loss when TCSC was optimally placed. Also the total system losses was reduced from 2.1252 P.U for real power and -29.3978 P.U for reactive power to 0.9756 P.U for real power and -32.811 for reactive power. It is, as well, observed that the voltage profile stability was maintained between 0.9p.u and 1.1p.u.

**Table 1. Line flows for the power system without facts device**

| From Bus | To Bus | Line | P Flow | Q Flow | P l0ss | Q loss |
|---|---|---|---|---|---|---|
| | | | [p.u] | [p.u] | [p.u] | [p.u] |
| Alaoji | Afam | 1 | 15.8197 | -4.0261 | 0.14739 | -8.6644 |
| Ph main | Afam | 2 | 3.263 | 0.63094 | 0.00059 | 1.3603 |
| Benin | Onitsha | 3 | 8.5123 | -0.55304 | 0.36966 | 0.74953 |
| Trans Amadi | Ph main | 4 | 3.263 | 0.72425 | 4e-005 | 0.09331 |
| Okpai | Onitsha | 5 | 4.4157 | -10.7271 | 0.02727 | -9.6088 |
| Onitsha | Alaoji | 6 | 14.8384 | 1.8667 | 1.1787 | 6.9329 |
| Onitsha | New haven | 7 | -1.2874 | -3.8477 | 0.27265 | -2.9977 |
| Benin | Delta | 8 | -2.7427 | 0.73335 | 0.03851 | -4.0233 |
| Sapelle | Benin | 9 | 3.4001 | -7.1253 | 0.03047 | -4.7189 |
| Aladja | Delta | 10 | -0.62913 | -0.47618 | 0.01921 | -4.3393 |
| Sapelle | Aladja | 11 | -2.1484 | -5.5077 | 0.04071 | -4.1815 |

**Table 2. Sensitivity index table**

| LINE | FROM (BUS) | TO (BUS) | SENSITIVITY INDEX $a_{ij}$ (60% COMPENSATION) |
|---|---|---|---|
| 1. | 3 | 1 | -236.2088 |
| 2. | 9 | 1 | -1273.90 |
| 3. | 4 | 8 | -66.0504 |
| 4 | 9 | 11 | -87.8280 |
| 5. | 7 | 8 | -53.0734 |
| 6. | 8 | 3 | 13.5765 |
| 7 | 8 | 6 | -18.9580 |
| 8. | 5 | 4 | -8.9334 |
| 9 | 10 | 4 | -32.8654 |
| 10. | 5 | 2 | -110.8873 |
| 11. | 10 | 2 | -15.7205 |

**Table 3. Line flows with FACTS devices placed optimally**

| From Bus | To Bus | Line | P Flow | Q Flow | P loss | Q loss |
|---|---|---|---|---|---|---|
| | | | [p.u] | [p.u] | [p.u] | [p.u] |
| Alaoji | Afam | 1 | 6.1971 | -0.79671 | 0.1752 | -8.6071 |
| Ph main | Afam | 2 | 3.263 | 0.63094 | 0.00059 | 1.3603 |
| Benin | Onitsha | 3 | 8.5121 | -0.57435 | 0.36946 | 0.74597 |
| Trans Amadi | Ph main | 4 | 3.263 | 0.72425 | 4e-005 | 0.09331 |
| Okpai | Onitsha | 5 | 4.4157 | -10.9472 | 0.0286 | -9.6067 |
| Onitsha | Alaoji | 6 | 4.5371 | 1.6323 | 0 | 3.469 |
| Onitsha | New haven | 7 | -1.2874 | -3.8531 | 0.27265 | -3.0031 |
| Benin | Delta | 8 | -2.7427 | -0.72978 | 0.03855 | -4.0236 |
| Sapelle | Benin | 9 | 3.2008 | -7.1425 | 0.03061 | -4.7183 |
| Aladja | Delta | 10 | -0.62905 | -0.47619 | 0.01921 | -4.3393 |
| Sapelle | Aladja | 11 | -2.5284 | -5.5077 | 0.04071 | -4.1815 |

## Conclusion

The results obtained from the simulations have shown that congested lines can be relieved by placing FACTS devices and that transmission line Onitsha – Alaoji is the optimal location to place TCSC in the South east Nigerian 11- bus network. Results obtained showed that placement of TCSC has additional effect of power losses reduction and voltage stability of the network.

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## Appendix

**Table A2. Existing power stations**

| S/N | NAME | Gen. MW | Gen. MVAR |
|---|---|---|---|
| 1 | Delta PS | 342.95 | 112.82 |
| 2. | Okpai | 441.57 | 104.84 |
| 3. | Sapele PS | 125.17 | -61 |
| 4. | Afam PS | 457.12 | 148 |
| 5. | Trans-Amadi | 32.63 | 18 |

**Table A3. Transmission line parameters for the south east 330kv network in Nigeria**

| Transmission Line Number | Line between buses and the number of circuits | | Length of line(km) | Line impedance | |
|---|---|---|---|---|---|
| S/N | From | To | | R (p.u) | X (p.u) |
| 1 | Onitsha | Alaoji | 138 | 0.049 | 0.042 |
| 2 | Onitsha | New haven | 96 | 0.0038 | 0.0284 |
| 3 | Benin | Onitsha | 137 | 0.0054 | 0.0405 |
| 4 | Delta | Benin | 107 | 0.0042 | 0.0316 |
| 5 | Sapelle | Benin | 50 | 0.0009 | 0.0070 |
| 6 | Okapi | Onitsha | 56 | 0.0005 | 0.0042 |
| 7 | Afam | Alaoji | 25 | 0.0006 | 0.0043 |
| 8 | Afam | PH main | 38 | 0.0015 | 0.0112 |
| 9 | P.H Main | Trans Amadi | 10 | 0.0004 | 0.003 |
| 10 | Sapelle | Aladja | 63 | 0.0025 | 0.0186 |
| 11 | Delta | Aladja | 30 | 0.0009 | 0.0072 |

Source: [7], [8]

**Table A4. Load Bus Data**

| S/N. | BUS NAME | ACTIVE | REACTIVE |
|---|---|---|---|
| **1.** | BENIN | -2.4000 | -1.1200 |
| **2** | ONITSHA | -1.0200 | -0.4400 |
| **3.** | ALADJA | -1.5600 | -0.8500 |
| **4.** | ALAOJI | -2.1600 | -1.0400 |
| **5.** | NEW-HAVEN | -1.1000 | -0.1800 |
| **6.** | PH Main | 0.0000 | 0.0000 |

Source: [7], [8]