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# SERIES COMPENSATION OPTIMISATION METHOD «SCOM» FOR THE LONG DISTRIBUTION LINES

Eder Fernandez R.     René Wamkeue     Nahi Kandil

Département des sciences appliquées, University of Quebec in Abitibi Temiscamingue
445 blvd de l'université, Rouyn Noranda, QC, J9X5E4
rene.wamkeue@uqat.ca

## ABSTRACT

In this paper, we develop an optimization method to determine the optimal series compensation ratio for a distribution network. The objective function consists of minimizing the voltage variation under several stability constraints. An initial power flow solution is used to evaluate the problem constraints formulated via algebraic equations and inequalities.
The validation and effectiveness of the optimization method have been demonstrated by means of simulation analysis using PSB Power System Blockset Program in conjunction with Simulink.

**Key Words:** Power flow, reactive power, Hunting, Series Compensation, Flicker, SSR and Simulation.

## 1. INTRODUCTION

In recent years the constant growth of the residential and industrials loads forced the companies to undertake new projects in the construction of the electrical supply networks and important investments in research for new technologies to improve the performance of the existing distribution networks. Several power quality issues such as poor voltage regulation, voltage flicker, reduction of power flow, harmonics distortion and the strong loads variations produced by motors starting which is the one of the most important aspects that leading the distribution network to instability[1, 2].
In the North of Québec, Canada, the distribution network of Hydro-Quebec has to supply rural areas characterized by the long distance lines. In the operating hours at full load starting of motors, crushers, winches, etc, produces a strong voltage drop. Series compensation have been selected as an appropriate technology to give and to avoid the perturbations caused by industrial loads such as mines and sawmills connected by long distance feeders. [3,4,7]. A principal disadvantage of series compensation is the occurrence of sub-synchronous resonance which are torsional stresses on the turbine-generator shaft. But many technologies are available today to solve this problem [10,11,12]. In this paper, we develop an optimization method to compute the suitable series compensation degree under various network constraints evaluated using initial power flow solution. The effectiveness of the proposed network analysis is confirmed through simulations.

## 2. SYSTEM DESCRIPTION

The investigated system configuration investigated is shown in Fig. 1. It consists of two subsystems interconnected by a distribution line.

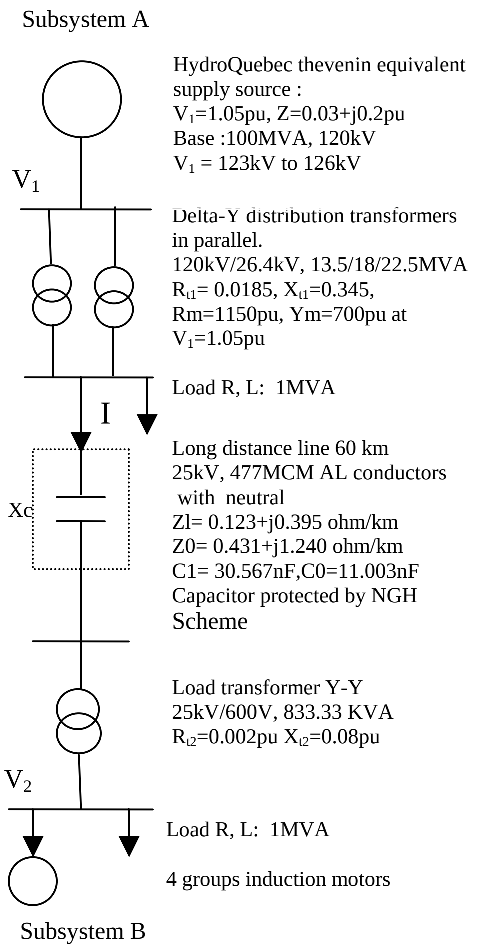


Fig. 1 System configuration

The operating frequency of the system is 60 Hz. At 25kV voltage level, the power is transmitted from subsystem A to B via distribution line compensated by a series capacitor.

The subsystem A is represented by a thevenin equivalent supply source and a load R,L of 1 MVA. The subsystem B by a load RL of 1 MVA and 4 groups of asynchronous motors at load, table 1.

Table1. Parameter of the motors groups

| Parameter | Group 1<br>2 motors | Group 2<br>3 motors | Group3<br>motors | Group 4<br>2 motors |
|---|---|---|---|---|
| Power HP | 400 | 450 | 375 | 400 |
| Rs $(\Omega)$ | 0.0868 | 0.0694 | 0.0214 | 0.08675 |
| Xls$(\Omega)$ | 0.2 | 0.16 | 0.0284 | 0.2 |
| Xm$(\Omega)$ | 6.795 | 5.435 | 1.938 | 6.795 |
| Xlr$(\Omega)$ | 0.0685 | 0.0548 | 0.0277 | 0.0685 |
| Rr' | 0.1645 | 0.1316 | 0.0482 | 0.1645 |
| JKg.m$^2$ | 4.93 | 6.16 | 18.6 | 4.93 |
| Torque Nm | 891.4 | 2605 | 1114 | 891.4 |

## 3. OPTIMIZATION METHOD FORMULATION

The optimization method developed in this paper is formulated such as given in [3]:

### 3.1 Objective Function

The objective function depends on the circuit parameters as the Voltage magnitude $V_2$, the load power factor ($\cos\theta$), the load magnitude P and Q, the inductive reactance of the feeder $X_L$ and capacitive reactance of series capacitor Xc [1]. The objective function can be minimized increasing the voltage profile at load $V_2$ and respecting all the stability constraints. Load can change from hour to hour, at strong load variations and second to second when motor are started. In this case, series capacitor will improve instantaneously the voltage quality at the loads downstream from the series capacitor [1,2]. According to equations (1) and (2) the demanded reactive and active power can be expressed as follows:

Active power : $P = V_2.I.\cos\theta$ (1)

Reactive Power : $Q = V_2.I.\sin\theta$ (2)

Using the equations (1) and (2), we obtain (3) to find (4). The criterion based on minimizing the voltage variation can be built using (4) as the objective function of the optimization process. This equation introduces the series compensation reactance Xc [3]:

$$\Delta V \equiv V_1 - V_2 \cong R.I.\cos(\delta-\theta) + X_L.I\sin(\delta-\theta) \quad (3)$$

$$\Delta V \cong \frac{P.R + Q.(X_L - Xc)}{V_2} = f(Xc) \quad (4)$$

$$\min f(Xc) = \Delta V \quad (5)$$

$$\text{h1:}\quad 0 \le \frac{Xc}{X_L} \le 100\% \qquad \text{h2:}\quad P_O \le P_N \quad (6)$$

$$\text{h3:}\quad 0 \le \frac{R}{X} \le 1 \qquad \text{h4:}\quad Xc \le x.X_L \quad (7)$$

$$\text{h5:}\quad KVA_{CC} \ge \frac{\alpha.100}{0.5} \qquad \text{h6:}\quad Q_L \le Q_{LO} \quad (8)$$

$$\text{h7:}\quad 0 \le x \le 60Km \qquad \text{h8:}\quad f = 60Hz \quad (9)$$

Where h is a set of eight network stability constraints defined as h1 series compensation degree and h2 maximum power transfer (6); h3 hunting phenomenon and h4 short circuit inversion current (7); h5 flicker voltage and h6 reactive power losses (8); h7 optimal series capacitor location and h8 Subsynchronous resonance (9). Those network stability constraints are defined in the next section.

### 3.2 Network Stability constraints

#### 3.2.1 Series Compensation degree h1

The degree of compensation is the ratio between the capacitive reactance of series capacitors and the inductive reactance of the distribution line. By degrees higher than 100%, it is said that the distribution network is overcompensated and the ferroresonance phenomenon is caused [1]. Series compensation degree is defined by (10) :

$$\tau = \frac{Xc}{X_L} \quad (10)$$

This constraint determines that $\tau$ =100% is the upper bound of the optimization method.

#### 3.2.2 Maximum Power Transfer h2

It is well known that series capacitors improve stability bounds and increase the power transfer capabilities. Depending on the series compensation degree, the transfer impedance can be reduced increasing the transmitted power limits[4,5]. Typically in the power flow analysis of transmission systems, the line resistance is neglected. For distribution networks the resistance must be included since its effects are relatively high [1,4]. An accurate mathematical calculation of the transmitted power is developed. The following equations (11) and (12) are used to develop this constraint [5]:

$$\mathrm{P} = \frac{V_1V_2}{Zl}\cos(\delta-\theta) - \frac{V_2}{Zl}\cos\delta \quad (11)$$

$$\mathrm{Q} = \frac{V_1V_2}{Zl}\sin(\delta-\theta) - \frac{V_2{}^2}{Zl}\sin\delta \quad (12)$$

$$\kappa = cos^{-1} FP;\ \ Q = P\,tan\ \kappa \quad (13)$$

Solving equations (11), (12) and (13), the equation (14) is obtained to compute $P$ as follows:

$$P^2 \sec^2 \kappa + P\left[\frac{2V_2(\cos\delta + \tan\kappa \sin\delta)}{Zl}\right] + \left[\frac{V_2{}^4 - V_1^2 V_2{}^2}{Zl^2}\right] = 0 \tag{14}$$

Solving the equation (14) and knowing that the equivalent reactance $Zl = R+j(X_L-X_C)$, the transmitted power is equal to (15):

$$P = \frac{-V_2{}^2 \cos(\delta - \theta)\cos\kappa \pm \cos k\sqrt{V_2{}^4 \cos^2(\delta - \theta) - (V_2{}^4 - V_1^2 V_2{}^2)}}{Zl} \tag{15}$$

Four different series compensation degrees have been computed to show the transmitted power performance along the line (see fig.2 and table 2).

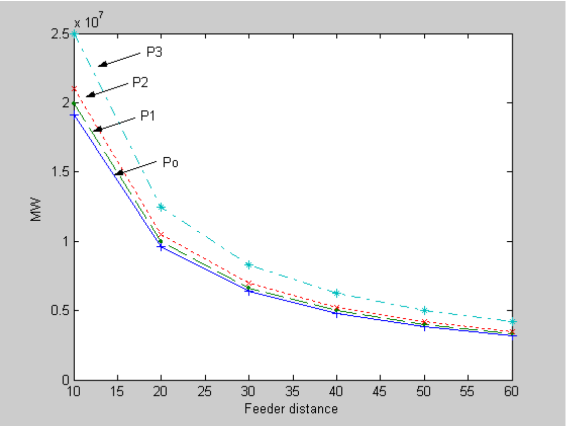


Fig. 2 Performance of power flow along the line

Table 2. Maximum power transfer

| Power | MW | $Xc\,(\Omega)$ | $\tau$ (%) |
|---|---|---|---|
| $Po$ | 2.5 | 0 | 0 |
| $P_1$ | 3.08 | 8 | 33.76 |
| $P_2$ | 3.29 | 13 | 55 |
| $P_3$ | 3.87 | 15 | 63.3 |

This constraint can be represented as an inequality (16):

$$P_O \le P_N \tag{16}$$

Where the initial value of transmitted power is $P_O$, and $P_N$ is the new power magnitude after applying different series compensation degrees [3].

### 3.2.3 Motors Hunting Phenomenon h3

Hunting is a disturbance of a lightly-loaded synchronous motor caused by switching of the power circuits and changes in load or excitation current of the motors [4]. But this phenomena is not limited to synchronous motors, in induction motors driving reciprocating loads, the application of series capacitors can cause hunting. The hunting can be predicted by the ratio of the dissipation energy of the feeder resistance to the energy storage capacity of the total feeder reactance (including the series capacitor). The distribution networks supplying rural areas present a relatively high *R/X* ratio of the long distance distribution cables [4]. The expression can be written as an inequality (17) as follows:

$$0 \le \left[\tan(\angle Zl) = \frac{R}{X_L - X_C}\right] \le 1 \tag{17}$$

To develop this constraint, it is necessary to evaluate this phenomenon using the numerical simulation to detect the oscillations of the mechanical speed(see figs 12 and 13). To avoid the hunting phenomena, $\tau$ can be between 0 and 66% (Xc=15.7$\Omega$). For the investigated distribution network fig. 1, the upper bound to avoid the hunting is 55% (Xc=13$\Omega$).

### 3.2.4 Short Circuit Current Inversion h4

Current Inversion is caused for a short circuit fault when the inductive reactance is less than the capacitive reactance of the series capacitor and the relay location is capacitive with respect to the source voltage due the capacitive magnitude in the fault loop [6]. The constraint is determined as the expression (18). Equivalent reactance of the line was founded capacitive to values bigger than $\tau$ =55% (Xc = 13$\Omega$).

$$Xc < X_L \text{ and } Xc > X_L - R \tag{18}$$

### 3.2.5 Flicker Voltage h5

The flicker is associated with an excessive voltage drop along the feeder reactance caused by a momentarily large current with an inherently low power flow. This phenomenon is usually detected when large motors start at the end of a feeder [4]. The procedure to quantify and develop this constraint begins calculating the flicker voltage using the equation (19) [7]:

$$\Delta V\% = \frac{KVAstart}{KVA_{CC}} * 100 \tag{19}$$

The flicker voltage to the industrial costumers is about 0.5 % at a frequency of 8Hz [7]. The demanded power at load can be solved using the starting *Id* and nominal current *In*, the performance $\eta$ and the starting class of motor $\beta$, equation (20).

$$KVAstart = \frac{HP.0.746.(Id/In).\beta}{\eta.PF} \tag{20}$$

The flicker frequency g[f(i)] can be computed using (fig 4). Flicker voltage is included in equation (19).

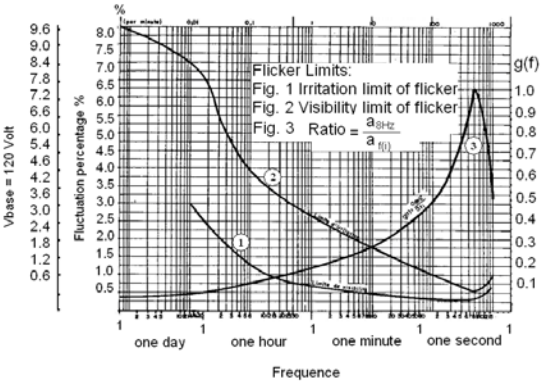


Fig. 4 Flicker Limits

The g[f(i)] is obtained from residential costumers in the periods of 1 hour, 1 minute and 1 second to build the curve 3 (fig. 4). Now, we calculate the $\alpha$ at each motor (21) and the $\alpha$ total, as equation (22) [7].

$$\alpha_i = \frac{HP.0.746W.\frac{Id}{In}.\beta}{\eta.FP}.g[f(i)] \qquad (21)$$

$$\alpha_{8Hz}\,(\mathrm{t}) = \sqrt{\sum_i a_8{}^2(t)} \qquad (22)$$

Solving (21) the minimal short circuit power at load to avoid the flicker is computed using (23) as follows:

$$KVA_{CC} \geq \frac{\alpha.100}{0.5} \qquad (23)$$

Now we compare the value calculated with (23) and the short circuit power from (24) to determine the minimal series compensation degree in which the short circuit power is minimal and the flicker is reduced.

$$KVAcc = \frac{V_2/\sqrt{3}}{\sqrt{(Rs+Rt+R)^2+(Xs+X_t+X_L-Xc)^2}} \qquad (24)$$

Where *Rs+jXs* is the equivalent impedance of the source and *Xt* the transformer impedance. This constraint allow to determine the minimal KVAcc, 14.6 MVA with $\tau$ = 21% ( Xc = 5$\Omega$).

### 3.2.6 Reactive Power Losses h6

Reactive power maintains the voltage to deliver active power through distribution lines. Series capacitors increase the reactive power and reduce the losses. A reactive power study is developed with different series compensation in the distribution network fig 1 [8]. Reactive and active power can be expressed developing the equation (25) as follows:

Knowing that: $V = V_1^2+V_2^2-2V_1V_2.cos(\delta-\theta)$

$$P + jQ = I^2(R+jX) = V^2\left[\frac{R}{R^2+X^2}\right] + V^2 j\left[\frac{X}{R^2+X^2}\right] \qquad (25)$$

This constraint can be written as inequality (26):

$$Q_L \leq Q_{LO} \qquad (26)$$

Where the initial value of reactive power losses are $Q_{LO}$, and $Q_L$ the new values after the application of different series compensation degrees.[3].

### 3.2.7 Optimal Series Capacitor Location h7

In this section a mathematical method has been developed based on the voltage variations at each side of series capacitor and load downstream. (see Fig. 5)[1,7].

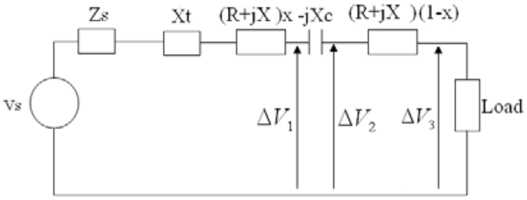


Fig.5 Single-line diagram of a radial circuit.

The circuit voltages upstream (27), downstream from the capacitor (28) and the load voltage (29) can be calculated using fig. 6, as follows:

$$V_1 = \frac{(1-x)Zl - jXc + Zc}{Zs + Zl - jXc + Zc}Vs \qquad (27)$$

$$V_2 = \frac{(1-x)Zl + Zc}{Zs + Zl - jXc + Zc}Vs \qquad (28)$$

$$V_3 = \frac{Zc}{Zs + Zl - jXc + Zc}Vs \qquad (29)$$

According to fig. 6, the expressions (30) determine the performance of series capacitor:

$$\Delta V_1\% \leq \Delta V_2\% \text{ and } |\Delta V_3\%| \leq |\Delta V_2\%| \qquad (30)$$

Solving (30), the resulting expression is developed in equation (31):

$$|(1-x)Zl - jXc + Zc| \geq |Zc| \qquad (31)$$

Replacing the equivalent reactance of the line Zl, the equation (31) results in the equation (32):

$$(1-x)(R+X_L)-Xc \geq 0 \qquad (32)$$

Solving the equations (32), the optimal series capacitors position *x* is computed as the equation (33), considering the resistance of the line as follows:

$$x \leq \frac{R+X_L-Xc}{R+X_L} \quad \text{to} \quad Xc < X_L \qquad (33)$$

### 3.2.8 Sub-Synchronous Resonance SSR h8

The distribution network investigated is equipped with a thyristor control reactor connected in parallel in order to protect series capacitor against SSR, fig 7. It is based on the scheme developed by Narian G. Hingorani known as

NGH-Scheme [9,10,11]. The protection consists of a damping scheme that measure the half-cycle of series capacitor voltage and if this half-cycle period exceeds a present period, the energy of the capacitor will be dissipated into a resistor shunting the series capacitor through two anti-parallel thyristor damping of the SSR.[9]. Using the steady state frequency response, we can identify a SSR about 7Hz ($\tau$ = 55%) removed it using NGH scheme (fig. 6).

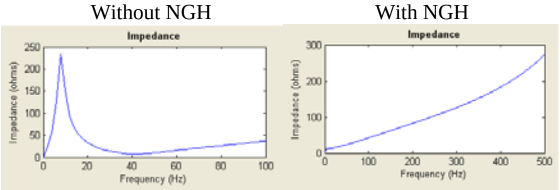
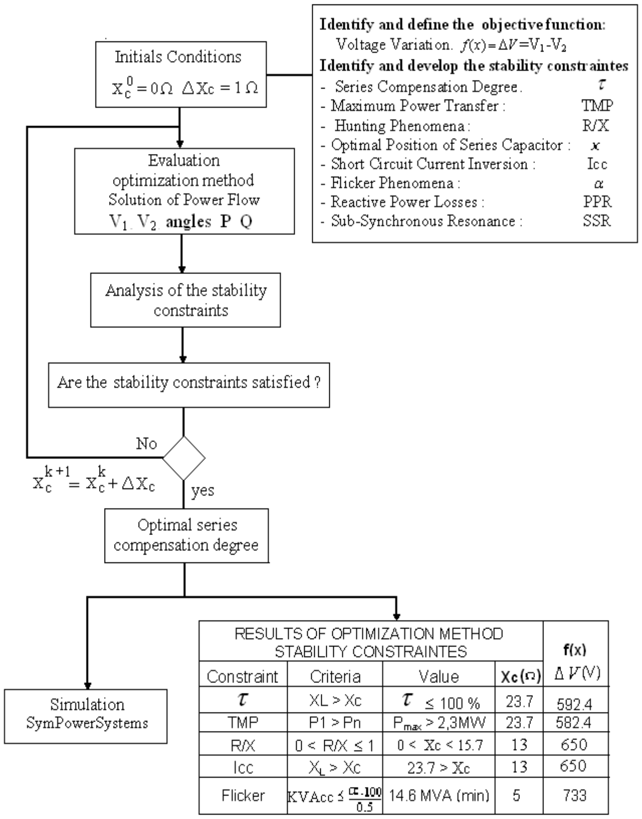


Fig.6 Elimination of SSR using NGH scheme for Xc=13Ω

## 4. OPTIMIZATION PROCEDURE

Step 1 Initials conditions.
Step 2 Identification and definition of the stability constraints and objective Function.
Step 3 Power flow solution.
Step 4 Evaluation of the constraints and the objective function to find the SCOR.
Step 5.Optimal series compensation rate $\tau$
Step 6 Results of the optimization method and simulation of typical tests



| RESULTS OF OPTIMIZATION METHOD STABILITY CONSTRAINTES | | | | f(x) |
|---|---|---|---|---|
| Constraint | Criteria | Value | Xc(Ω) | $\Delta V$(V) |
| $\tau$ | XL > Xc | $\tau \le 100$ % | 23.7 | 592.4 |
| TMP | P1 > Pn | $P_{max}$ > 2,3MW | 23.7 | 582.4 |
| R/X | 0 < R/X ≤ 1 | 0 < Xc < 15.7 | 13 | 650 |
| Icc | $X_L$ > Xc | 23.7 > Xc | 13 | 650 |
| Flicker | $KVAcc \le \frac{\alpha \cdot 100}{0.5}$ | 14.6 MVA (min) | 5 | 733 |

Fig.7 Optimization method

## 5. OBTAINED RESULTS: THE SERIES COMPENSATION OPTIMIZATION REGION "SCOR"

### 5.1 THE SCOR:

The performance of the optimization method can be observed using an operation region modeling based on the lower and upper bounds of the stability constraints. The objective function is included on this region to evidence the minimization. As shown in fig. 8, the constraints about the maximum power flow and reactive power losses have been accomplished. The constraint h3 about Hunting phenomenon reduces the SCOR to $\tau$ = 66 %. The constraint h4 limits the SCOR to $\tau$ = 55% (Xc=13Ω), and the equivalent reactance of the line is positive. The constraint h5, flicker voltage, define the minimal $\tau$ in which this phenomenon is avoided. Fig. 8 resumes the previous network stability constraints as follows:

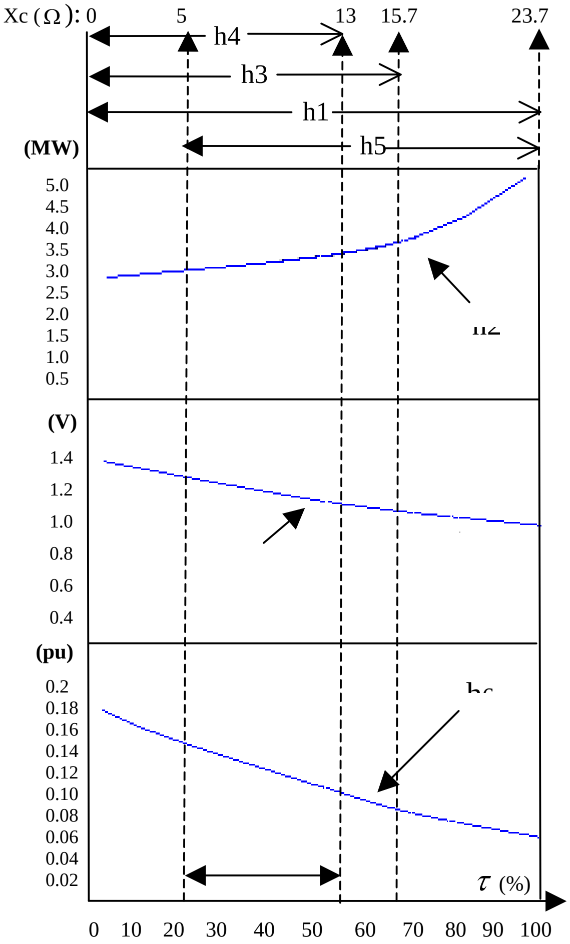


Fig.8 Series Compensation Optimization Region SCOR

### 5.2 NETWORK PERFORMANCE PREDICTION

The simulations were developed considering the analytical results obtained by means of the Series Compensation Operation Region, SCOR. The electrical torque and the mechanical speed of the motors group 2 is simulated at different conditions to observe its performance during the typical perturbations produced in the distribution network. Two scenarios have been evaluated considering the lower and upper bound of the SCOR. Hunting phenomenon also was detected during the perturbations. The first scenario is a single phase to ground short circuit fault occurs on phase A between the transformer $X_{t1}$ and the series capacitor at t= 1s. The series compensation increases the fault current flow due to the reduction of the reactance from the source to the location of the fault. The strong reduction in the mechanical speed is observed during the fault. The performance of the mechanical speed for $\tau$ = 55% is better than $\tau$ = 21% (fig. 9). The elevation of the magnitudes and the duration of the oscillations in the electrical torque are observed when $\tau \geq$ 21% (fig. 9). For the second scenario, a sudden change of mechanical torque is applied in motors group 2 at t= 3s. The mechanical speed is reduced strongly when the torque is doubled. In this perturbation the performance of $\tau$ = 55% is observed (figs. 9 and 10). The instantaneous return to the steady state of the voltage is also observed after the fault conditions, fig. 11.

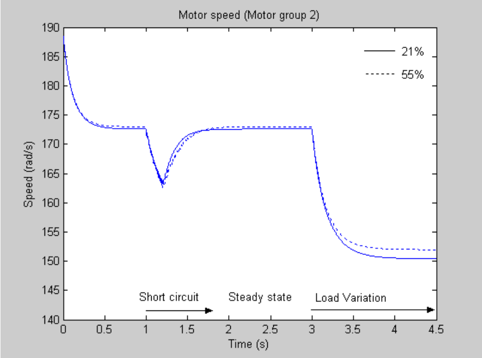


Fig.9 Mechanical speed of heaviest motors (group 2)

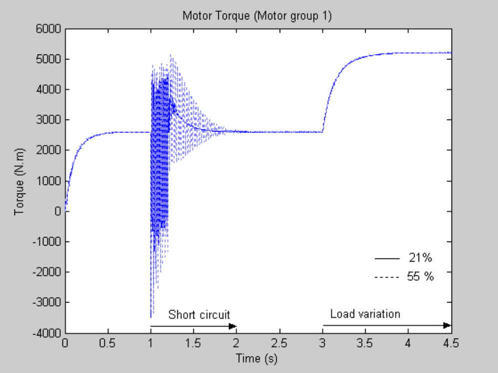


Fig.10 Electrical torque of heaviest motors (group 1)

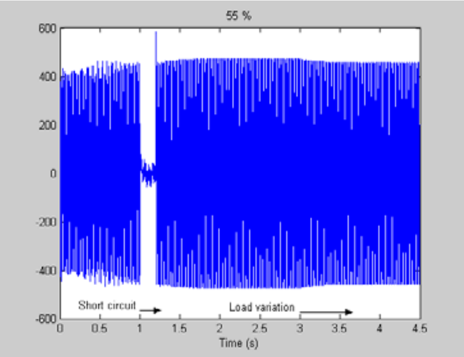


Fig. 11 Load voltage n short circuit load variation

As shown in figs. 12 and 13, mechanical speed is reduced in both scenarios but the steady state conditions are maintained when we compensate at $\tau$ =55% (Xc= $13\Omega$). After the perturbations, mechanical speed oscillates producing the hunting to $\tau$ > 55%.

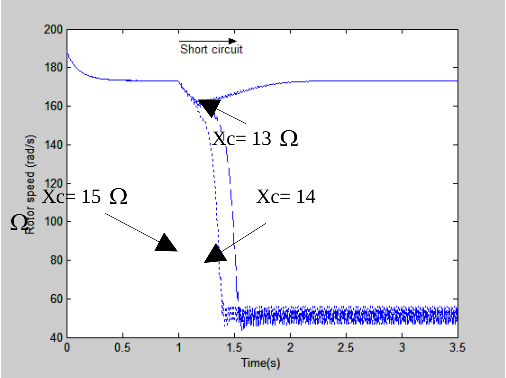


Fig.12 Mechanical speed of heaviest motors (group 2) during a short circuit at t= 1s.

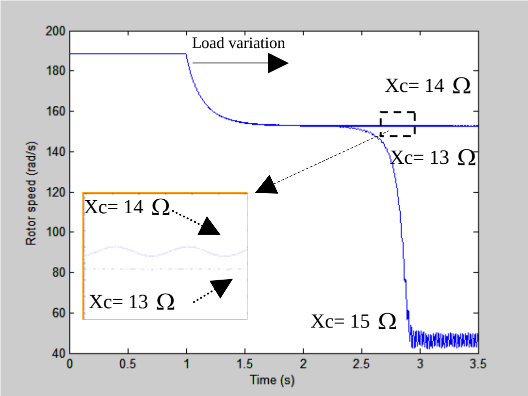


Fig.13 Mechanical speed of heaviest motors (group 2) during a strong load variation at t= 1 s.

## 6. CONCLUSIONS

In this paper, a new optimization method is proposed to find the optimal series compensation degree and the suitable location of series capacitor along the feeder. The modeling of the SCOR is a strategy to visualize the performance of the series compensation degree in a distribution network. In addition, the instantaneous effect of series capacitor has been simulated during start-up transient and steady state operation. For the case of investigated distribution network, Hunting was the constraint to determine the upper bound of SCOR, $\tau = 55\%$ ($X_c = 13\,\Omega$). The flicker voltage determined the minimal value to compensate the distribution network, $\tau \geq 21\%$. The series compensation degree $X_c = 13\ \Omega$ can be implemented to 35 Kms from the source, reducing $\Delta V$ to 15V (600V) (table 3) or to 605V(25kV), increasing the voltage load and maintaining the distribution network in stability conditions.

| Series compensation | Load voltage (600V) | Load voltage (25kV) |
|---|---|---|
| $X_c = 0\,\Omega$ | 577.6 V | 24.03kV |
| 21 % ($X_c = 5\ \Omega$) | 582.4 V | 24.23kV |
| 55% ($X_c = 13\,\Omega$) | 584.6 V | 24.32kV |

Table 3. Voltage at load bus $V_2$

## ACKNOWLEDGMENTS

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