Series Compensation for a Hydro-Quebec Long Distribution Line

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Abstract. The paper focuses on the use of series compensation in a Hydro-Quebec long distribution line. The basic theory of a series compensation is outlined together with operation network constraints that should be respected in practical applications. The study is done on a 60km radial distribution line supplying both industrial and residential customers. Three levels of compensation rate have been tested, 0% (non compensated), 36% and 60% in both frequency response and time domains. Simulation results greatly attest the effectiveness and the practicability of the series compensation of long distribution line in transient and steady state improvement of the voltage profile and fluctuation reduction.

Key words series compensation, long distribution line, induction motors, simulation

1. Introduction

In the region of Abitibi-Temiscamingue, located in the north of Quebec (province of Canada), customers are spread all over the region and separated by long distances. Therefore, Hydro-Quebec uses long distribution lines, especially in rural areas, to provide electricity for both residential and industrial loads (mines and saw-mills industries generally). Customers suffer from the flicker and reduction of the line voltage due to heavy motors starting in those of industrial loads. As a solution to this typical problem, Hydro-Quebec has been considering series compensation for these long distribution lines.

For a long time, series capacitors have been successfully used in transmission lines for improving system performances [1-2]. In distribution systems, the main benefit of series capacitors is the natural voltage control achieved by changes in load current. The voltage sag and the sudden electrical energy interruption are the most important disturbances of the power quality in electrical system [3]. The disturbance is common in longer distribution lines, such as rural electrical systems where long distribution lines are used for feeding both industrial and residential loads. A starting motor draws a large current with a poor power factor and causes a momentary voltage dip along the feeder. The voltage dip is sudden and typically lasts only a few seconds until the motor reaches the design speed. It is a typical problem that must be addressed whenever industrial and residential loads are connected to the same feeder through a long distribution line [4-7].

The distribution series capacitors have been recognized as an economical solution to the voltage flicker problem. Adding a series capacitor to a radial circuit reduces the reactance of that circuit. The series capacitor acts as a voltage regulator that provides a boost in voltage at the capacitor location. Moreover, this boost in voltage is instantaneous and continuous, which makes the concept a natural choice where rapidly changing loads are present [5-10].

However, when using series capacitor compensation of distribution lines, careful consideration needs to be given to capacitor location, ferroresonance, ohmic reactive value, transient behavior, short circuit withstand, subsynchronous resonance and capacitor protection.

The main objective of this paper is to outline the practical application of series compensation in a potential 60km long distribution line for the voltage profile improvement. The theoretical approach of line compensation using capacitor banks is outlined together with network limitations that should be rigorously respected in practices. The paper proposed simple and practical method without complex mathematical regression algorithm to obtain good compensation degree for maximum power transfer and the suitable line capacitor placement that improves system performance. Three levels of compensation rate 0% (non compensated), 36% and 60%, obtained from network constraints, have been tested. The applied contingencies were the starting of unloaded asynchronous motors of a given mine industry and sudden step change in the load torque of asynchronous motors in normal operation. Simulation results using Matlab-Blockset Toolbox for previous values of series capacitance have been investigated, compared and discussed. Among others interesting results, simulations have proved the effectiveness of the method on the profile improvement of the load bus voltage, the mechanical speed and electrical torque during induction motor transients and steady state operation.

2. Series Compensation Principle

Let consider the circuit in Fig.1, that represents a typical series compensated radial circuit, where R_l, X_l, X_c are respectively the line resistance, the line reactance and the reactance of the series capacitor. The approximated voltage drop per phase from source to load obtained from phasor diagram of Fig.1 can be written as given in (1). Defining the active and reactive power absorbed by the load in (2), the voltage drop (1) can also be expressed as given in (3) where τ is the compensation ratio of line that should be kept less than 100%. More often, the total net ($X_l - X_c$) is inductive. The line is overcompensated if $X_l \leq X_c$. The overcompensation is to be avoided in order to prevent the line from increasing ferroresonance phenomenon [9;11].

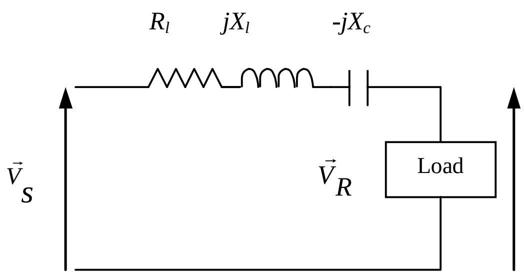

Fig.1: Single-line principle diagram of a series compensated radial circuit with a lumped load

Equation (3) shows that the voltage regulation provided by the series capacitor is continuous and instantaneous. In case of of voltage fluctuations due to large variations of the load, a series capacitor will improve the quality at the loads downstream from the series capacitor. Fig.2 shows the influence of the series capacitor on the voltage profile of a radial power distribution line with inductive loads.

$$\Delta V = R_l I_l \cos\varphi_R + (X_l - X_c) I_l \sin\varphi_R \quad (1)$$

$$P_R = V_R I_l \cos\varphi_R ; \quad Q_R = V_R I_l \sin\varphi_R \quad (2)$$

$$\Delta V = \frac{P_R R_l + Q_R (X_l - X_c)}{V_R} ; \ \tau = 100 \frac{X_c}{X_T} \% \quad (3)$$

$$S_R = V_R I_l ; \qquad P_{loss} = R_R (I_l)^2 \quad (4)$$

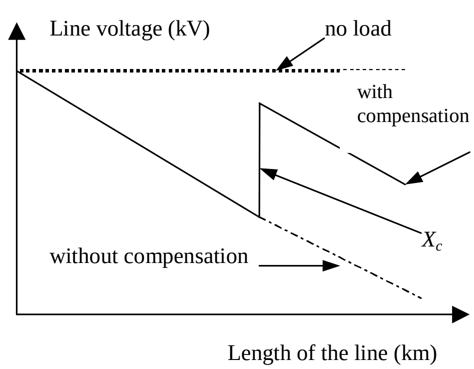

Fig.2: Voltage profile for a radial circuit with series capacitor.

X_T is the total reactance of the line. Assuming constant receiving end apparent power, series capacitor improves power factor seen by the sending end by bringing negative VAR (- $X_C I_l^2$). The line losses (4) are also reduced.

In fact, since the receiving end voltage V_R will increase, from first part of (4) the line current will decrease to reduce line losses. The influence of the series capacitor on the receiving end voltage can be calculated from (5). The theoretical maximum voltage is given by (6)

$$\frac{V_R}{V_S} = \frac{S_R}{S_s} = \frac{\sqrt{P_R^2 + Q_R^2}}{\sqrt{P_R^2 + (Q_R - Q_C)^2}} \quad (5)$$

$$\frac{V_R}{V_S} = \frac{S_R}{P_R} = \frac{1}{\cos\varphi_R} \quad (6)$$

When introducing a capacitor into a line, the fault level at the transformer and the load side of the capacitor will be increased. During system faults on the load side, the capacitor will be exposed to currents and voltages much higher than normal load conditions. In addition, the circuit becomes potentially highly ferroresonant. Ferroresonance can cause the generation of heavy currents and over voltages that can damage power system components. The capacitor and the transformer are at great risk of damage if ferroresonance occurs. To manage these potential hazards, a detailed analysis on the use of series capacitors in distribution lines is needed [2, 6].

3. System Topology

The studied system is a long distribution line such as could be encountered in the north of Hydro-Quebec network (Fig.3). It comprises four parts:

1- The Hydro-Quebec bulk power: modeled from Thevenin equivalent observed from the distribution transformer, its data are given in Fig.3

2- *Two distribution tap-changer transformers in parallel*: 120kV/25kV, delta-Y connected to step down the voltage for the distribution line. Two transformers are needed here for security purpose in case where one of both breaks down. They are identical and theirs parameters are listed
in the Table.1 above

Table.1 Transformer characteristics

Designation	Parameter value
Selected base power	22.5MVA
Z1 (direct-sequence)	0.037+j0.69 pu
Z0 (zero-sequence)	0.037+j0.69 pu
Ym (admittance) at Vn=1.05pu	0.0014 pu
Xm=1/Ym(magnet. rect.)	741 pu
Rm (magnet. Resitance)	1150 pu
R (resiatance)	0.0185 pu
X(reactance)	0.345 pu

3-The distribution line: The line conductors are 20km to 60km aerial, 25kV, 477 MCM AL with Z1=0.123+j0.395 (Ω/km), Z0=0.443+j1.240 (Ω/km),

4- Loads: Since the present work focuses on distribution long lines supplying mines and saw-mill industries in the north of the Quebec, the loads frequently met in such cases are (R,L) loads for residential and asynchronous motors for industrial loads. A 1MVA, 90% power factor (R,L) load is put in parallel with four groups of 4-poles asynchronous motors which characteristics are listed in Table.2. These loads have been connected to the distribution system through a 25KV/600V, 833.33KVA, 60-Hz,R=0.002 pu, X=0.08 pu load transformer. The saturation characteristics of transformer are given in Table.3

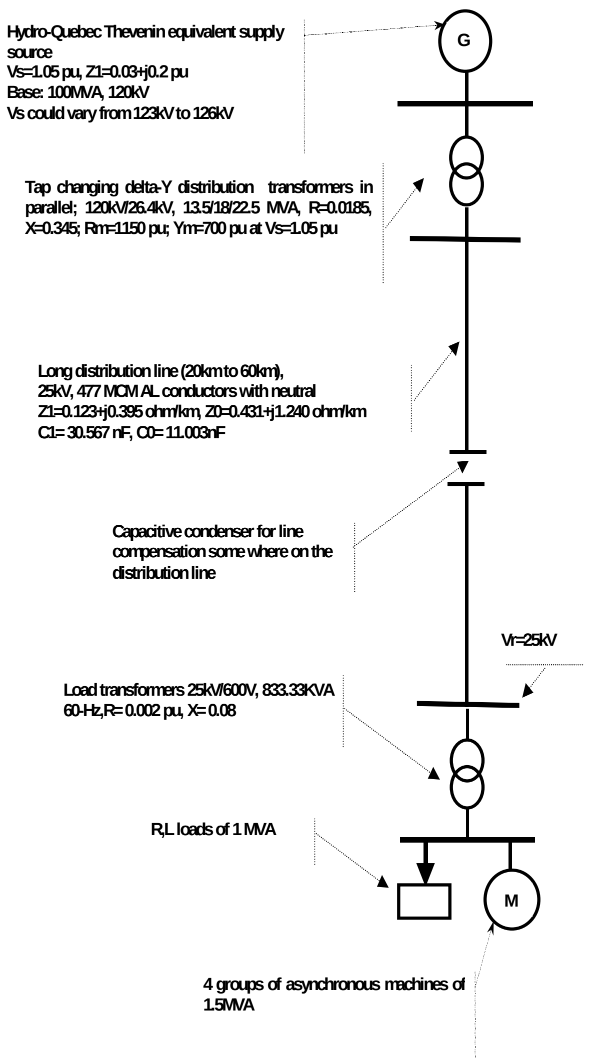

Fig.3 Topology of the studied network

Table.2: Characteristics of asynchronous motors

Designation	group 1 2motors	group 2 4 motors	group 3 2 motors	group 4 2 motors
Power (HP)	600	600	250	200
Rs (Ω)	0.0119	0.0214	0.0694	0.08675
Xls(Ω)	0.0547	0.0284	0.16	0.2
Xm(Ω)	2.451	1.938	5.435	6.795
Xlr'(Ω)	0.0547	0.0277	0.0548	0.0685
Rr'(Ω)	0.0085	0.04815	0.1316	0.1645
J kg.m^2	31.4325	18.6	6.16	4.93

Table.3: Saturation characteristics of load transformer

I (pu)	0	0.0018	0.0033	0.0045	0.0072	0.058	1
Flux (pu)	0	0.8998	1.0507	1.0997	1.1508	1.301	1.6

4. Cased Studied

Several scenarios lead to the determination of the minimum compensation rate that should maintain the stability limit of the distribution network. The practical constraints to be considered are the followings:

Criterion 1: The value of the condenser for minimum allowed short-circuit power (70MVA for mine industry and 30MVA for saw-mill with another industry on the same line): This rule of the thumb prevents the voltage from excessive fluctuations. The condenser values computed from the formula (7) are listed in column 2 of Table 4 [12].

$$Psc_{\min}(X_c) = \frac{\left(V_R\sqrt{3}\right)^2}{\sqrt{\left(R_s + R_l\right)^2 + \left(X_s + X_l - X_c\right)^2}} \qquad (7)$$

Table 4: Minimum compensation criterions

Criterion $Psc_{\min} \geq$	20km line	60km line	Xc limit Criterion 1	P_{Rmin}. limit criterion. 2	P_{Rmin}. limit criterion. 3
70MVA (mine)	X		Xc=2.9Ω	7.4MVA	32.6MVA
70MVA (mine)		X	Xc=22.7Ω	3.9MVA	2.8MVA
30MVA (saw-mill)	X		none	5.9MVA	946MVA
30MVA (saw-mill)		X	Xc=8.9Ω	2MVA	7.5MVA

where $Psc_{\min}$ is minimum short-circuit power required, R_s, X_s are the source Thevenin equivalent resistance and reactance. For example, from this criterion, $Xc = 2.9\,\Omega$ is required for a 20km line mine industry and $Psc_{\min}$ is sufficient without compensation for a saw-mill industry as shown in the Table 4.

Criterion 2: The maximum power flow with a given constraint on reactive power (PF=0.95 if the load is greater than 5MVA and PF=0.9 for the others cases) .

Those values of power factor are set by commercial rules. This criterion allows to compute the maximum flow in the line without voltage regulator. In this study, since the total load is 2.5MVA, P.F=0.9 will be chosen. The obtained results computed from (8-9) are listed in column 4 of Table 4.

$$\max P_R(X_c) = \frac{-V_R^2\cos(\delta-\varphi_R)\cos\varphi_R + A\cos\varphi_R}{\sqrt{R_l^2 + (X_l - X_c)^2}} \qquad (8)$$

$$A = \sqrt{V_R^2 V_R^2 - V_R^4 \sin(\delta - \varphi_R)} \qquad (9)$$

where δ is the compensated line impedance angle. As given by column 4 of Table 4, the maximum power flow in the line without voltage regulator is 3.9MVA for a mine industry $X_C = 22.7\Omega$ and 2MVA for a saw-mill industry for $X_C = 8.5\Omega$

Criterion 3: Voltage should be within allowed limits along the distribution line, as set by national requirement (CSA). This criterion insures that the voltage to other consumers connected along the line is acceptable. The computed values are given in column 5 of Table 4.

Criterion 4: The capacitance of the condenser will be lower than the whole line reactance to avoid the overcompensation of the line . This criterion is easy to evaluate.

Criterion 5: The resonance frequency between the network and loads should be avoided. Assuming constant impedance load, the network becomes straightforward. Calculations have shown that for a mine, the maximum compensation to avoid resonance with a power flow of 3.9MVA is $Xc = 7.4\Omega$; for a saw-mill this value is 2MVA for $Xc = 14\Omega$. Finally the compensation constraint limit are resumed in Table 5:

Table 5: Compensation limit values

Cases studied	Psc	PR	Xc(Ω)
Mine 60km	≥70MVA	≤3.9	$Xc = 22.7\Omega$
Saw-mill 60km	≥30 MVA	≤2	8.5≤ Xc ≤14
Mine 20km	≥70 MVA	≤7.4	2.9 ≤Xc ≤3.8

5. Simulation results

A. Computation of steady state conditions:

Initial conditions of steady state are computed using power flow toolbox of Matlab-Blockset software. For the four groups of asynchronous motors, the steady state torque has been calculated for three values of compensation rate (Table 6). The short-circuit power has been also obtained for three values of compensation rate (Table 7)

Table 6:Steady state motor torque

No of group	Compensation rate	Steady state torque
Motor group 1 2X300 HP	none	2411(N.m)
	36%(Xc=8.5Ω)	2409(N.m)
	60%(Xc=14Ω)	2408(N.m)
Motor group 2 4X150 HP	none	2618(N.m)
	36%(Xc=8.5Ω)	2605(N.m)
	60%(Xc=14Ω)	2597(N.m)
Motor group 3 2X125 HP	none	1123(N.m)
	36%(Xc=8.5Ω)	1114(N.m)
	60%(Xc=14Ω)	1110(N.m)
Motor group 4 2X100 HP	none	898.2(N.m)
	36%(Xc=8.5Ω)	891.4(N.m)
	60%(Xc=14Ω)	887.7(N.m)

A small discrepancy can be easily observed between theoretical computed values and those obtained by simulation. Simulations have taken into account the shunt capacitive modeling of the line that is not considered in analytical computation of the short-circuit power.

Table 7 Short-circuit power Psc

Series compensation	Psc (analytical)	Psc (simulation)
none	22MVA	23MVA
36%(Xc=8.5Ω)	31MVA	32MVA
60%(Xc=14Ω)	40MVA	43MVA

Table 8: Short-circuit peak currents (Isc)

Series compensation	Isc at the sending end	Isc at the end of line
none	756.3A∠-44.09^0	762.6A∠-44.24^0
36%(Xc=8.5Ω)	1061A∠-37.49^0	1066A∠-37.63^0
60%(Xc=14Ω)	1407A∠-29.56^0	1412A∠-29.71^0

Table 8 shows that increasing the compensation rate increases the short-circuit power of the distribution line. This important effect avoids voltage fluctuations. Table 9 gives the load currents. It can be observed that with compensation, short-circuit currents are high. The short-circuit current is greater at the receiving end of the line than near the substation. It is due to the contribution of the shunt capacitors of the line model that little increases the compensation rate of the line.

Table 9: Steady state currents and voltages at the load

Series compensation	Load current (peak)	Load voltage(peak)
none	3481 A	433.1 V
36%(Xc=8.5Ω)	3450 A	447.2 V
60%(Xc=14Ω)	3433 A	452.6 V

B. Steady state frequency response at the load

In order to analyze oscillations of the network, frequency response simulations have been done for three cases studied (0%, 36% and 60%). Interesting results have been obtained. At the load, a sub-synchronous resonance is observed between 7Hz and 8Hz as shown by Figs. 4 for the two given compensated rates. The amplitude of sub-synchronous resonance increases with compensation rate. A resonance frequency near 730 Hz is found in all scenarios.

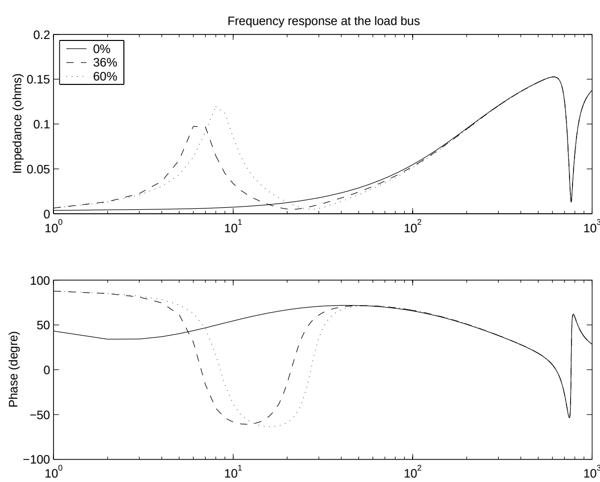

Fig. 4: Frequency response analysis of the compensated network during starting of unloaded induction motors

C. Starting of unloaded asynchronous motors

The starting test when all groups of motors are unloaded has been done in order to appreciate the impact of series compensation on transient performances of industrial induction motors.

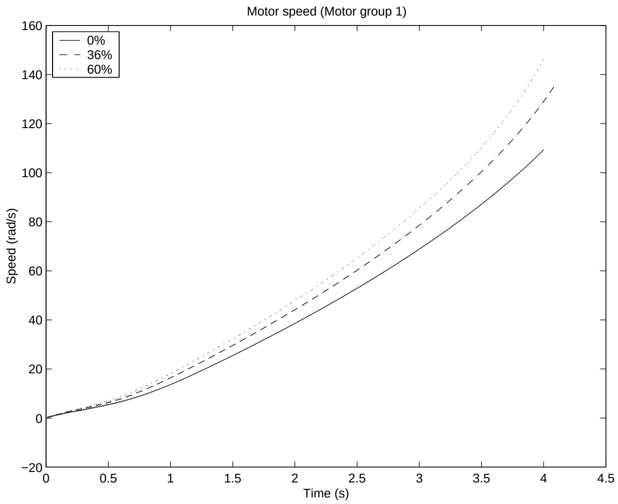

Fig.5: Mechanical speed during starting of heaviest unloaded induction motors (group 1)

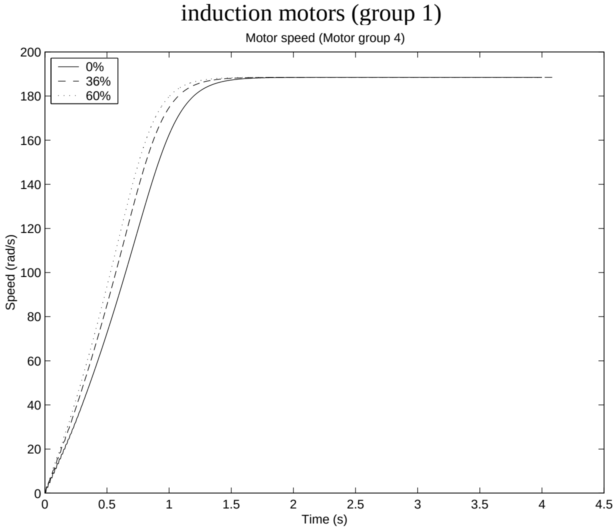

Fig.6: Mechanical speed during starting of lightest unloaded induction motors (group 4)

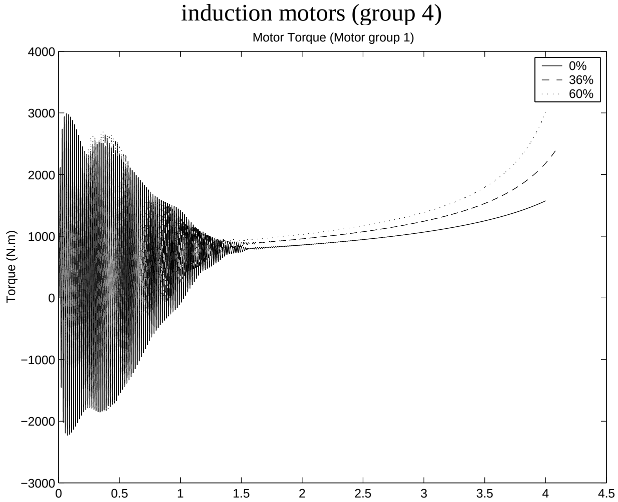

Fig.7: Electrical torque during starting of heaviest unloaded induction motors (group 1)

The improvement level of the voltage at 600V bus bar is also observed. Motors of group 1 show very long starting time due to their large inertia constant compared to the those of others groups which are less heavy. For example motors of group 4 (Figs 6 and 8) successfully start. It is interesting to observe that series compensation diminishes the starting time of motors. It acts here on speed and torque variables of motors as a PI regulator by increasing the rise time of transient period and by reducing the steady state error. Since motors are unloaded, the steady state electrical torque is zero (Fig.8). The improvement of the voltage profile is shown in Fig.9 where 60% compensation rate provides the best voltage level.

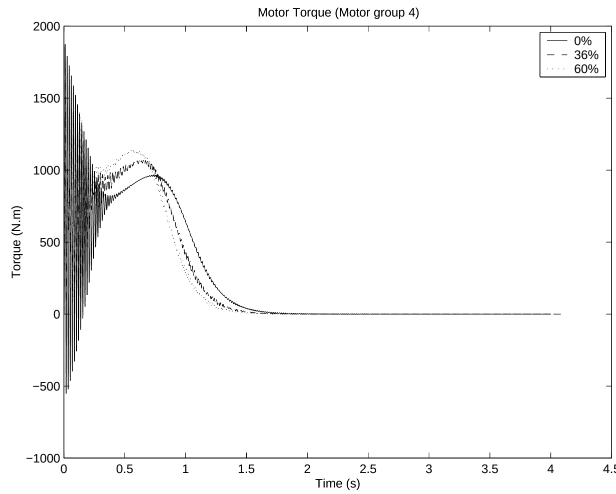

Fig.8: Electrical torque during starting of lightest unloaded induction motors (group 4)

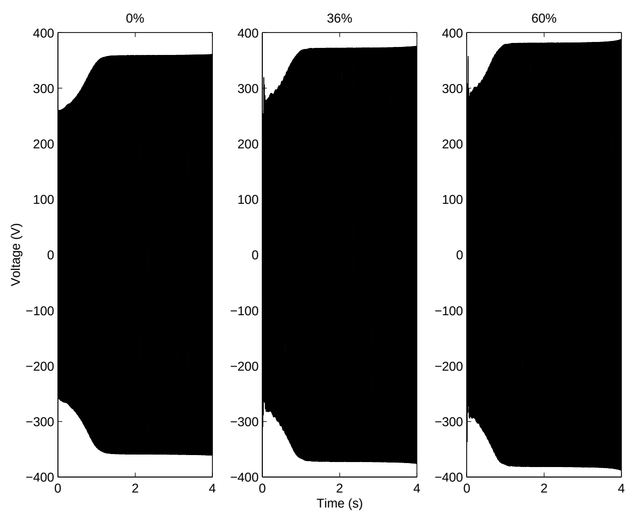

Fig.9: Voltage profile at the load bus of compensated network during starting of unloaded induction motors

D. Sudden change of motors mechanical torque

The step increase of the electrical torque of groups of induction motors has been tested as shown by figures below. The effects of series compensation are well illustrated by this test (see Figs.11 to 15). Motors of uncompensated network (0%) show difficulties to operate when their load is increased. They can not follow the new steady state solicited. Theirs speed and electrical torque decrease drastically during the step change in torque as shown on figures. The profile of voltage at the load bus as observed on Fig. 15 is very bad in this case.

In contrast, for compensated network, the motors behavior during the test is very good. The load bus voltage profile appears stable both in transient and steady state phases (Fig. 15). For a 60% compensation rate,

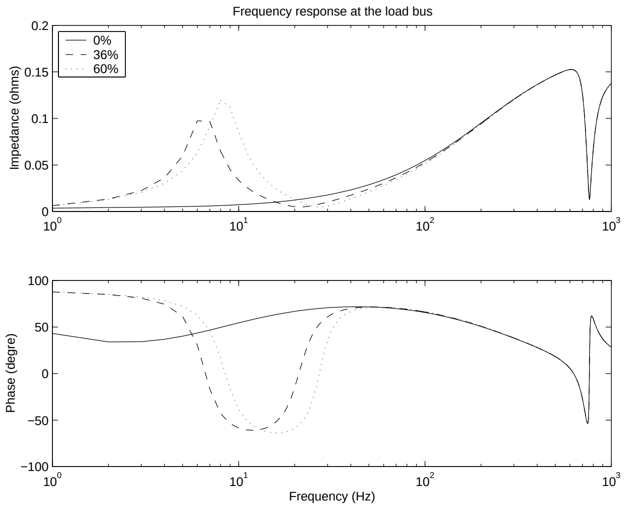

Fig. 10: Frequency response analysis of the compensated network during step increase of electrical torque of loaded induction motors

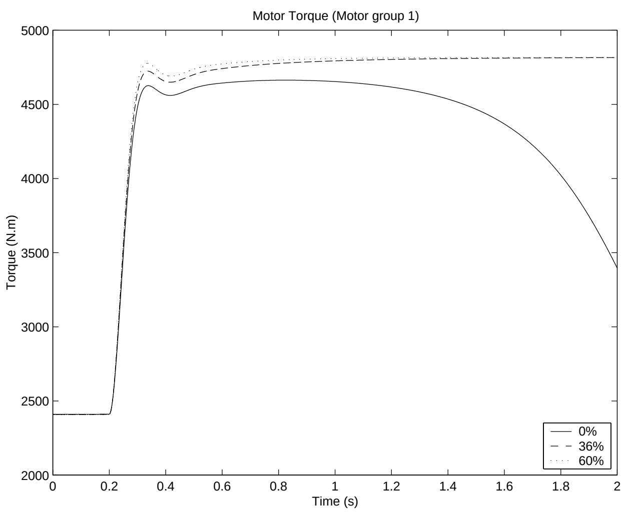

Fig.11: Electrical torque during step increase of electrical torque of heaviest loaded motors (group 1)

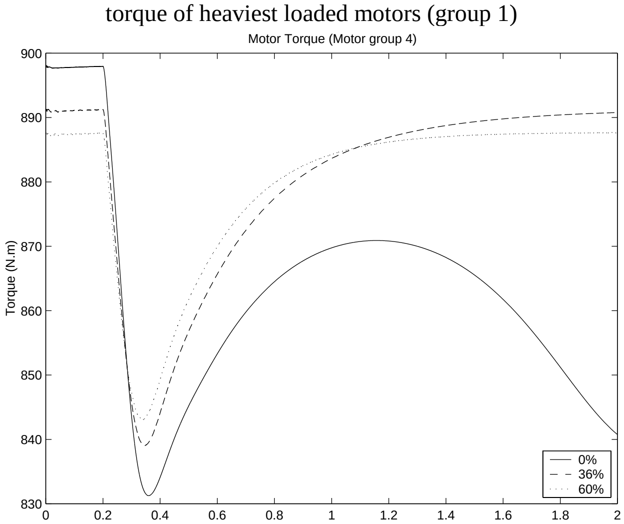

Fig.12: Electrical torque during step increase of electrical torque of lightest loaded motors (group 4)

the voltage profile is better than for 36%. Once more, as it has been previously mentioned, the series compensation behaves here as PI regulator for electrical torque and mechanical speed variables. It greatly reduces transient period and steady state error. Thus, the steady-state and dynamic stability of the network are both well improved.

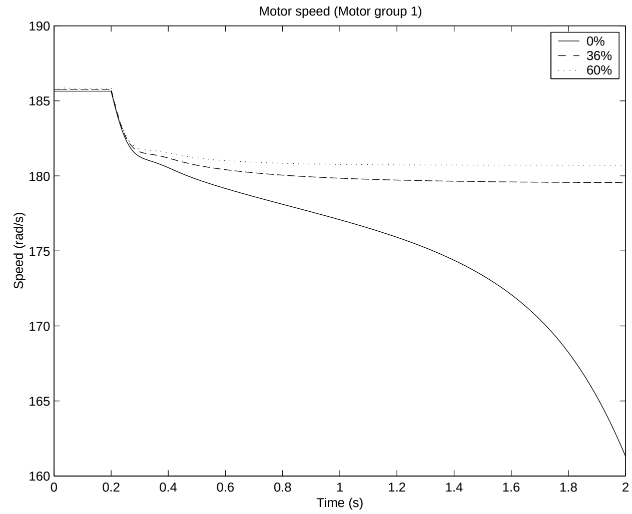

Fig.13: Mechanical speed during step increase of electrical torque of heaviest loaded motors (group 1)

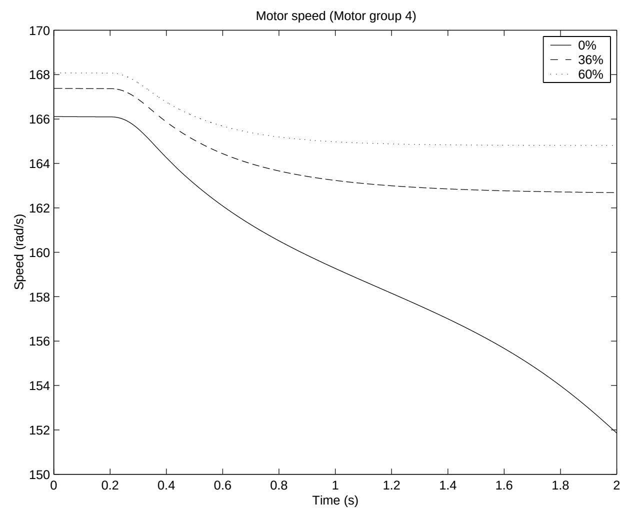

Fig.14: Mechanical speed during step increase of electrical torque of heaviest loaded motors (group 4)

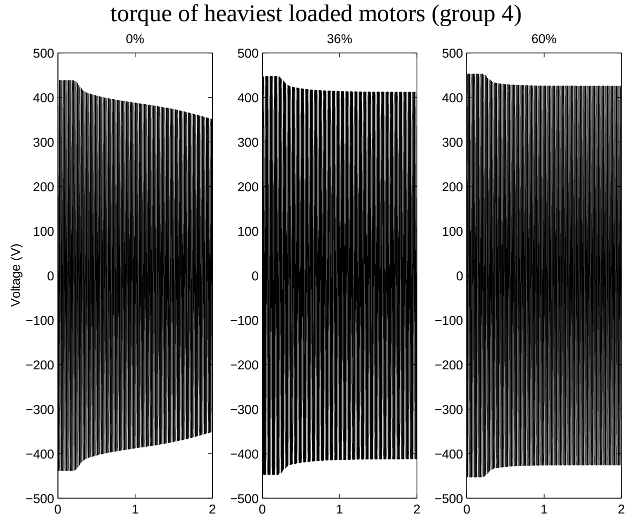

Fig.15: Voltage profile at the load bus of compensated network during step increase of electrical torque of induction motors

6. CONCLUSION

This work propose a practical and useful method to obtain the series compensation of a radial long distribution line. Simulation examples applied on a 60km Hydro-Quebec's distribution line supplying a mine industry have proved the effectiveness of the method on the profile improvement of the load bus voltage during induction motor start-up transient, steady state operation and step change of electrical torque. It has been well shown that the compensation technique acts as PI regulator on mechanical speed and electrical torque variable improvement of induction motors. The voltage improvement level increases with the compensation rate. But, practical constraints should be carefully considered in order to respect stability limits of the network and ferroresonance phenomena. This constraint limits brings us to obtain two extreme levels of compensation ratio for successful network compensation (36% and 60%) for the present study. But, what is the optimal value of the compensation rate? It is certainly between the previously extreme values. The present paper can not answer to this interesting question. A pertinent answer needs a solution based on optimization process under network practical constraints including the sub-synchronous resonance investigation. It's the focus of our future paper.

References

[1] J. S. Hedin and L. H. Paulsson, ''Application and evaluation of a New Concept for Compact Series Compensation for Distribution Lines'', in *12th International Conference on Electricity Distribution*, vol. 1, Birmingham, UK, May 17-21 1993, Conf. Publ. no. 373, pp. 1.22/1-5.

[2] S. A. Miske, '' Considerations for the Application of Series Capacitors to Radial Power Distribution Circuits'', *IEEE Transactions on Power Delivery*, vol. 16, no. 2, April 2001, pp. 306-318.

[3] S. R. Silva, '' Fast Series Compensator for Voltage Sag Correction'' , *IEEE International Electric Machines and Drives Conference Record, IEMDC'1997*, Proceeding of the IEEE International Electric Machines and Drives Conference, IEMDC, May 18-21, 1997, Milwaukee, WI, USA, p TC3 8.1-8.3.

[4] L. Morgan, J. M. Barcus, and S. Ihars, '' Distribution Series Capacitor with High-Energy varistor'', *IEEE Transactions on Power Delivery*, vol. 8, No., 3, July 1993, pp. 1413-1417.

[5] Minicap: Series Compensation of Distribution Lines, Västeräs, Sweden, 1991.

[6] R. A. Barr and D. Platt, '' Use of a Saturating Choke in the Series Capacitor Compensation of Distribution Lines'', *IEE Proceedings Generation, Transmission and Distribution*, v 144, no. 1, Jan., 1997, pp. 75-79.

[7] General Electric Co., *Distribution Series Capacitor: Application and design Considerations*, Schenectady, NY, 1991.

[8] L. O. Larsson, J. Samuelsson, J. J. Lombard, P. Berneche, and G. Allard, ''Application of a new concept for a compact series capacitor scheme for distribution networks'', Canadian Electrical Association, Distribution Section, Protection, Control and Substations Session, Engineering and and Operating Division, Vancouver, March 1995.

[9] ASEA, Series Capacitors for Distribution Networks, 1961.

[10] M. V. D. Lat, G. Kundu, and G. Bonadie, '' Overvoltage Protection Scheme for Series Capacitor Banks on High Voltage Distribution '', *IEEE Trans.*, vol. PWRD-5, no. 3, pp. 1459-1465, July 1990.

[11] P.M Anderson and R. G. Farmer, *Series Compensation of Power Systems.*

[12] Alpha Oumar Barry, Marie-Hélène Cloutier, Gilles Allard, '' *Impact de la compensation série sur le fonctionnement des moteurs à induction*", rapport IREQ, 16 Mars 1999.