Distribution Series Capacitor Application for Improved Motor Start and Flicker Mitigation

D. McCarrel, R. Bahry, A. Folkesson, IEEE Member and P. Bérubé, IEEE Member

***Abstract*- Voltage flicker can become a significant problem for power distributors when large motor loads are connected in remote locations. Installation of a series capacitor in the feeder strengthens the network and allows these loads to be connected to existing lines, avoiding more significant investment in new substations or new distribution lines.**

This paper describes a real-life application of a distribution series capacitor in Alberta, Canada where a long feeder is compensated to reduce flicker caused by infrequent start of large motors. To ensure performance within established feeder operating parameters, network simulation tools are used in design and engineering of the series capacitor. Overvoltage protection system and methods to detect and overcome problems related to subsynchronous resonance during start of large motors is also described.

This paper concludes that using distribution series capacitors is an effective and inexpensive method for network operators to connect large motor loads at the extremities of long distribution lines.

I. Introduction

The reactive power balance in an electrical network is regulated by the power system itself, power lines and electrical motors being the major users of reactive power, capacitors and synchronous machines being the contributors.

Only the active power produced by the active current is utilized at the point of consumption. The reactive power does not contribute to the conversion into useful power but is still necessary to be able to extract and use the active power.

The reactive power can be produced locally, by introducing series capacitors, to improve active power transfer by reducing the "electric length" of the line.

This paper presents a real application case. The Bassano series capacitor (March, 2005) was installed in an existing 25 kV feeder in FortisAlberta's distribution network in southern Alberta, Canada. The paper discuss several issues with regards to this application, such as:

- reasons for installing series compensation
- location in the circuit, degree of compensation
- protection by triggered gap
- flicker due to motor start
- damping of sub-synchronous resonance

A. Basic Theory

The basic theory of application of series capacitors is best demonstrated with the help of simple circuit and related phasor diagrams.

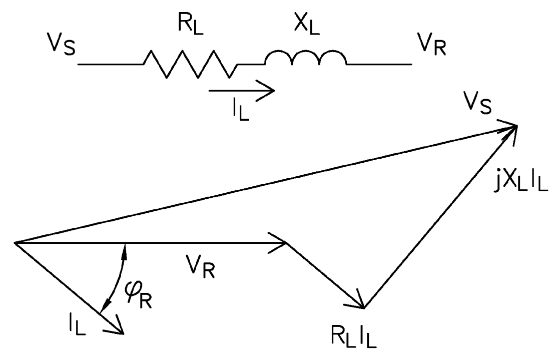

Fig. 1. Distribution line segment without series capacitor and related phasor diagram.

The voltage drop per phase along the line can be given as:

$$V_S - V_R = R_L I_L \cos\varphi_R + X_L I_L \sin\varphi_R \qquad (1)$$

Inserting a series capacitor in the circuit will counteract the inductive voltage drop with a phasor in the opposite direction:

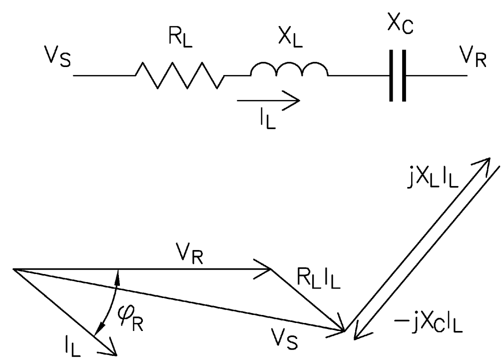

Fig. 2. Distribution line segment with series capacitor and related phasor diagram.

Fig. 2 above represents a typical series compensated radial circuit giving the total reactance in the circuit as:

$$X = X_L - X_C \qquad (2)$$

The resulting voltage drop can now be expressed as:

D. McCarrel and R. Bahry are with FortisAlberta Inc., Distribution Planning Section, 700, 801 – 7th Avenue SW, Calgary, T2P 3P7, AB, Canada

A. Folkesson and P. Bérubé are with ABB Inc., Systems division, 8585 route Transcanadienne, St-Laurent, H4S 1Z6, QC, Canada

$$V_S - V_R = R_L I_L \cos\varphi_R + (X_L - X_C) I_L \sin\varphi_R \qquad (3)$$

The voltage drop along the line has decreased due to the insertion of the series capacitor. Consequently the voltage at the receiving end has increased. If the power consumed by the load in the receiving end remains constant it also means that the line current has decreased.

For a fluctuating load it is important to note that the resulting voltage improvement is completely governed by the actual load current in the line, i.e. the series compensation is inherently instantaneous and self-regulating.

A complete description of the basic theory for application of series capacitors in distribution networks is given in [1] where the following areas for application are discussed:

- improvement of the voltage profile
- reduction of voltage fluctuations
- reduction of required feeder reactive power input
- reduction of the circuit losses
- division of current between parallel circuits
- support during motor start

II. Bassano Series Capacitor Application

A. FortisAlberta, network and customers

FortisAlberta is a distribution network owner and supplier of electrical power to customers within 60% of the Province of Alberta in Canada. Alberta has a population of 3 million people and a surface area of 661,190 km^2 (256,000 sq miles). FortisAlberta has approximately 95,400 km (59,365 miles) of distribution circuits and serves 390,000 customers. Load growth averages 4% per year in the service area. Distribution feeders are long and radial in nature. The average length of a feeder is 45 km (28 miles) with the longest feeders approaching 100 km (62 miles). These long lines result in very low short circuit levels at the extremities of the distribution feeders.

The largest group of consumers is industrial, notably Oil and Gas producers. These customers utilize large motors ranging in size from 100 hp to 5000 hp that are usually located at the extremities of the distribution feeders. Due to low short circuit levels at these locations, this creates challenges for motor starting.

B. Voltage flicker assessment

FortisAlberta utilizes a load flow program, CYMDIST, to assess the distribution system capability to start a large motor while satisfying voltage flicker guidelines. The purpose of the voltage flicker guidelines is to ensure that the voltage fluctuation associated with motor starting by one customer does not create problems for other customers. Generally, this means that voltage fluctuation during infrequent motor starting should not exceed 5 % at the primary of the customer transformer.

C. Series capacitors in distribution networks

Over the last 11 years, FortisAlberta has installed seven series capacitors in different distribution feeders for the specific purpose of allowing large motors to be connected near the feeder extremities. The series capacitor ratings ranged from 8.1 ohms to 20 ohms. The installations have been very successful, as there have been minimal problems, to date. Fig. 3 shows a typical series capacitor installation.

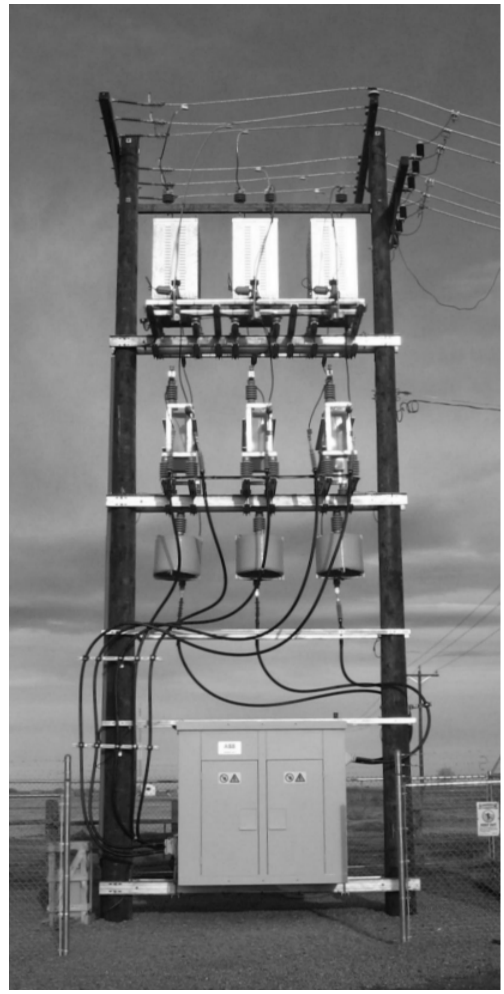

Fig. 3. 25 kV series capacitor installation at Bassano, AB, Canada.

D. Bassano series capacitor

Recently, a customer application resulted in a requirement for the installation of an additional series capacitor. In the Bassano service area in southern Alberta, FortisAlberta installed a new service to connect a 1750 hp squirrel cage induction motor for an Oil and Gas customer. The location of the customer site is approximately 43 km from the closest substation. The three phase distribution line from the substation to the large motor site utilizes 13.2 km of existing 397 MCM, 11.4 km of existing 266 MCM and 18.2 km of new 3/0 ACSR overhead conductor. The resulting short circuit level at the primary of the customer transformer is 26 MVA. As a rule of thumb, in order to meet the FortisAlberta voltage fluctuation guideline of 5 %, the rated power of the motor (hp) times 0.1 should be less than the short circuit level

(MVA) at the site. Consequently, at this site with a short circuit level of 26 MVA, a motor less than 250 hp can be started without any motor starting aids while still satisfying FortisAlberta's voltage fluctuation guideline.

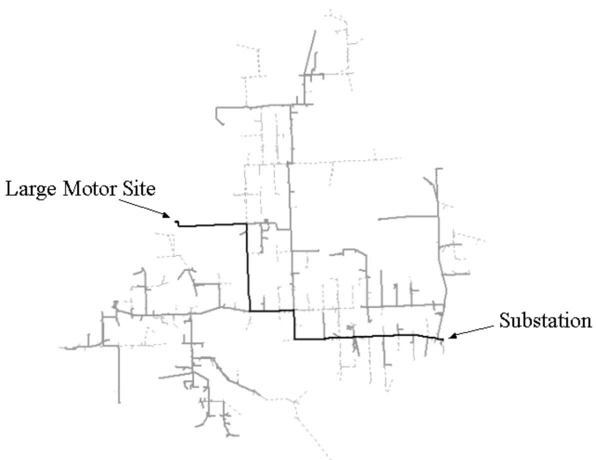

Fig. 4. The feeder during steady state operation. The line route from substation to the new motor load is shown in black and the adjacent line sections are shown in grey.

For this motor, the customer installed an autotransformer capacitor assisted starting aid. The autotransformer is set at 65% tap and the starting capacitor size is 3 MVAR. During motor starting with the starting aid, the calculated voltage fluctuation approaches 9% at the primary of the customer transformer and 12.4% on the secondary of the transformer. This exceeds FortisAlberta's flicker guideline of less than 5% at the primary of the transformer and could lead to complaints from other customers.

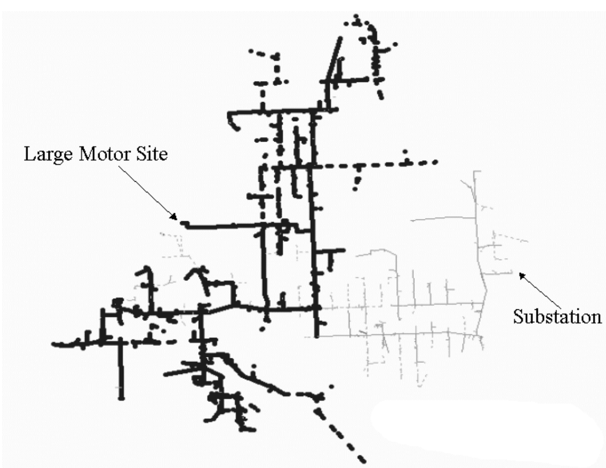

Fig. 5. Motor start without the series capacitor. A large part (highlighted sections) of the feeder area shows voltage fluctuations greater than 5%.

E. Location and Degree of Compensation

The degree of compensation (k) is usually derived from the voltage profile that is desired along the circuit and the location of the series capacitor. It is defined as the ratio between the series capacitor impedance (X_C) and the total inductive reactance (X_{EQU}) from the source to the location of the series capacitor:

$$k = \frac{X_C}{X_{EQU}} \cdot 100\% \tag{4}$$

For distribution network applications, it is often of interest to choose a relatively high degree of compensation in order to accomplish a desired voltage profile along the line. However, the choice of a high degree of compensation may lead to the appearance of undesired resonance phenomena.

For the Bassano application the location of the series capacitor was established by determining the location on the feeder where the voltage fluctuation approaches 5% when modeling a motor start. A 7.5 Ω series capacitor installed at a distance of 9.5 km (6 miles) from the substation improves the short circuit level to 36 MVA. The series capacitor also reduces the voltage fluctuations to 4.4% at the primary of the customer transformer and 8% at the secondary, when starting the 1750 hp motor using the autotransformer-capacitor assisted starting aid.

This meets the voltage fluctuation guideline of less than 5%. The feeder map (Fig. 6) now shows virtually the whole network without highlighted sections.

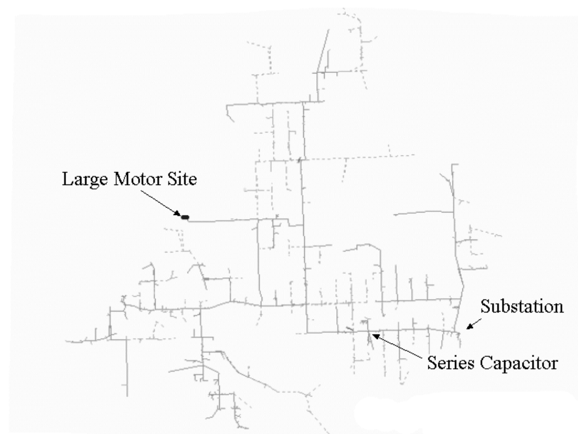

Fig. 6. Motor start with the series capacitor in service, only a small section of the feeder has voltage fluctuations above 5%.

The total inductive system reactance upstream of the series capacitor is 6.44 Ω. Using the above equation (4) gives a degree of compensation of 116%. As mentioned earlier, any compensation factor above 100% requires extra caution with regards to increased risk for subsynchronous resonance. Allowing overcompensation in this case increases the necessity for using subharmonic protection in combination with a parallel damping resistor.

After defining the location and size of the series capacitor, further simulations focusing on network load flow and motor start were conducted in order to verify the ratings.

III. Overvoltage protection

One of the most important factors to be considered in any series capacitor installation is the protection of the capacitors against damage due to overvoltage. In the event of line faults occurring on the load side of the series capacitor installation, a fault current will flow in the capacitor thus subjecting it to overvoltages.

Bypass gaps and varistors used alone or in combination are normally used in parallel with the series capacitor to control the magnitude and duration of capacitor overvoltages.

The Bassano series capacitor includes a gap protection device where the sparkover is initiated by a trigger circuit.

The voltage trigger level is set by a Metal Oxide Varistor, which is selected based on the limit voltage of the actual capacitor bank. When the capacitor voltage increases to the pre-set trigger level, a current starts to flow through the triggering circuit and after 500-1000 μs a fully developed arc is transferred to the main electrodes of the spark-gap. The arc remains between the main electrodes until the by-pass breaker is closed, approximately 80 ms later.

The arc is optically detected and used as a closing signal for the by-pass breaker.

The design of the triggered gap allows the distance between the main electrodes to be set large enough to avoid sensitivity to external atmospheric conditions and electrode wear.

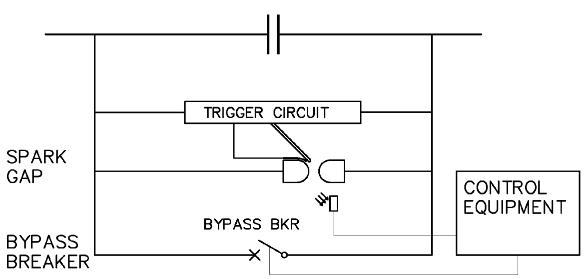

Fig. 7. Schematic representation of overvoltage protection with precision triggered gap.

IV. Sub-Synchronous Resonance

Most of the resonance problems that can occur while using series capacitors in distribution systems can be related to two different types of resonance phenomena, which are:

- Self-excited sub-synchronous resonance during start of asynchronous machine
- Ferroresonance due to transformer ratio

The sub-synchronous resonance (SSR) phenomenon occurring during motor start is investigated in this report by means of dynamic simulations using the transient analysis simulation program PSCAD/EMTDC.

A. Self-excitation of motors during start

The combination of a capacitor and an inductance create a series resonant circuit. For a series compensated power system, the frequency of oscillation of this resonant circuit is almost always subsynchronous, say from 10% to 90% of the fundamental frequency. For a circuit with an inductive load, such as a motor, the motor reactance is an element in the equation that determines the total circuit inductance, and hence the resonant frequency of the circuit. The existence of a subsynchronous frequency has been known to create problems in the starting of large motors, which is called self-excitation. A detailed analysis of this phenomenon is found in reference [4].

This problem is more likely to occur if the motor is large enough to cause a voltage dip on the circuit during motor start greater than 10%, and if the resistive load on the downstream side of the series capacitor is less than 10% of the motor rating. Also the following unfavorable factors increase the risk of self-excitation:

- Low network and line resistance
- Low source voltage level in p.u.
- High moment of inertia of the motor load
- High mechanical moment of the motor load
- High degree of compensation

The presence of parallel loads to the motor is advantageous due to increased damping in the circuit.

B. Mitigation

There are several measures available to prevent this sub-synchronous (SSR) phenomenon. The most common are discussed below.

Temporary by-pass of the series capacitor during starting sequence.

In most cases, this is not an acceptable solution if the voltage drop in the circuit is too high with the capacitor by-passed. In many cases, one of the purposes of the series capacitor is to improve the motor voltage during starting.

Permanent connection of a parallel damping resistor.

With a judicious selection of the resistor value, the resonance phenomenon can generally be eliminated. A permanently connected resistance results in power losses.

Temporary insertion of a parallel damping resistor.

As for the above measure, this solution will generally suppress the resonance phenomenon without the disadvantage of creating continual power losses. However, some kind of control system is required to switch the damping resistor in and out according to a defined control scheme.

For the SSR mitigation method using a damping resistor, its size should be carefully selected. Analysis of the networks characteristics and specific precaution rules will determine the risk of SSR and the resistance selection. In the literature, a value of R_P = 5 to 10 times X_C is recommended. For the identified cases where the SSR has a higher probability of occurring, a dynamic simulation for each individual application is required to judiciously select the damping resistor.

V. SSR Detector

Using temporary insertion of a damping resistor in parallel with the series capacitor requires a device for detection of harmonic oscillations in the network. The device used for the Bassano series capacitor is able to detect such oscillations and immediately insert the resistors to protect the capacitor bank as well as other equipment connected to the system.

The input signals to the detector are the line currents from two phases upstream from the capacitor.

The following protection and control functions are included in the SSR Detector:

1. Subharmonic protection. This is the principal function of the detector. The line current input is filtered in the control system and the level of sub synchronous resonance is detected. The output signal is used to switch in the parallel resistors for damping of the harmonic oscillations. The series capacitor will remain in service during the damping operation allowing the capacitor to improve conditions during motor start.
2. Fundamental frequency resonance protection. Resonance at fundamental frequency may occur, especially in case of overcompensation. The output signal from this function is used to operate the by-pass breaker.
3. Current control. At low load current the risk for self-excitation during motor start is augmented. This function will keep the resistor in parallel with the capacitor until a minimum load current is flowing. To prevent continual switching due to load fluctuations this circuit includes a hysteresis characteristic.
4. Back-up protection. This function will close the by-pass breaker in case the inserted parallel resistor did not damp the resonance.
5. Emergency by-pass. In a case where the switch controlling the damping resistor circuit did not respond to a signal from the subharmonic protection, this function will close the by-pass breaker after a time delay.
6. Automatic reinsertion. When the resonance event (sub harmonic, fundamental frequency resonance or self excitation) has elapsed the by-pass breaker or the parallel switch is automatically opened. To avoid an uncontrolled sequence of open and close operations, this function also includes a protection that will not allow more than a set number of by-passes. After this number is reached, the series capacitor will stay by-passed.

VI. Simulations

A. *Load flow simulation*

A load-flow analysis was performed with the PSCAD Power System Simulation tool for verifying the performance of the distribution feeder with and without the series capacitor inserted.

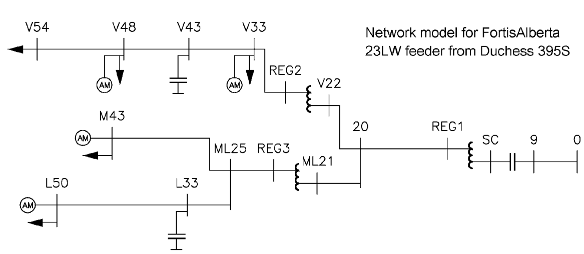

Fig. 8. Simulation model for the Bassano feeder. The node designations denote the distance (km) from the substation.

Fig. 8 shows the network model used in the simulations. The new motor added to the system, called "Large Motor Site" in Fig. 4 to 6, is located at node M43. The feeder has three existing voltage regulators used for improving the voltage profile along the line.

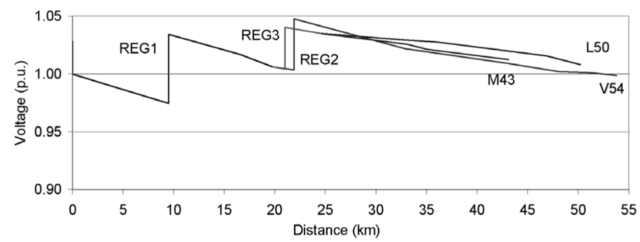

Fig. 9. Voltage profile graph without series capacitor. The regulators are adjusted to give a reasonable voltage level at the extremities of the feeder.

Fig. 9 shows the feeder voltage profile without the series capacitor installed. In steady state conditions the regulators are adequate for keeping the voltage at an acceptable level even with the additional new motor running.

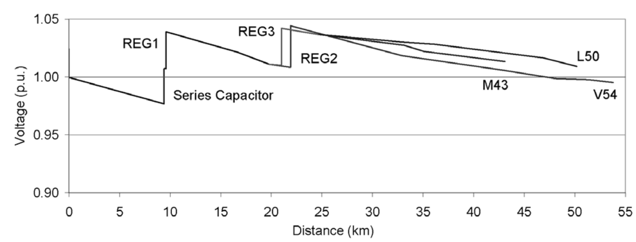

Fig. 10. Voltage profile graph with series capacitor. The regulators are re-adjusted to give a reasonable voltage level at the extremities of the feeder.

Fig. 10 shows the impact of the series capacitor installation on the voltage profile along the line. Note that the series capacitor is appropriately sized and does not result in high voltage when the large motor is running.

B. *Motor Start Dynamic Simulation*

The distribution network model used for the motor start simulation is the same as the one used for the load flow analysis (Fig. 8), however the motor under study is now modeled using the simplified d-axis equivalent circuit shown in Fig. 11.

Motor model

The induction motor under study has the following characteristics:

Power:	1750 hp
Voltage:	4000 V
Speed:	3580 rpm
Poles:	2

And the equivalent parameters for this motor are:

Stator resistance, R_1:	0.0063 p.u.
Stator leakage reactance, L_1:	0.106 p.u.
Magnetizing reactance, L_{MD}:	3.09 p.u.
Rotor resistance, R_{2D}:	0.005 p.u.
Rotor mutual reactance, L_{2D}:	0.07 p.u.

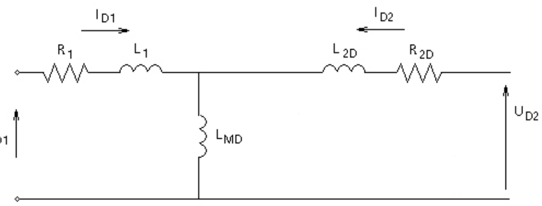

Fig. 11. Induction motor simplified d-axis equivalent circuit

Analysis

As mentioned in section IV-A above, the self-excitation phenomenon can cause motor starting problems, which may eventually cause the motor to stall. An efficient countermeasure to this problem is the insertion of a damping resistor in parallel with the series capacitor.

Different dynamic simulation cases are performed to carefully size the damping resistor and define the insertion control scheme.

This is accomplished using the transient analysis simulation program EMTDC run under the PSCAD graphical user interface, which allows easy modeling and analysis of complex dynamic phenomenon.

In the Bassano case, a 1750 hp motor located 43 km from the source sub-station is started under different load conditions. The motor is equipped with a soft-start device, but for the purpose of this study, the worst case using direct start has been considered.

The aim of the first case is to reproduce the self-excitation phenomenon.

In this case (case #1), the 1750 hp motor is starting with low parallel load (feeder current approximately 35 A) and no damping resistor.

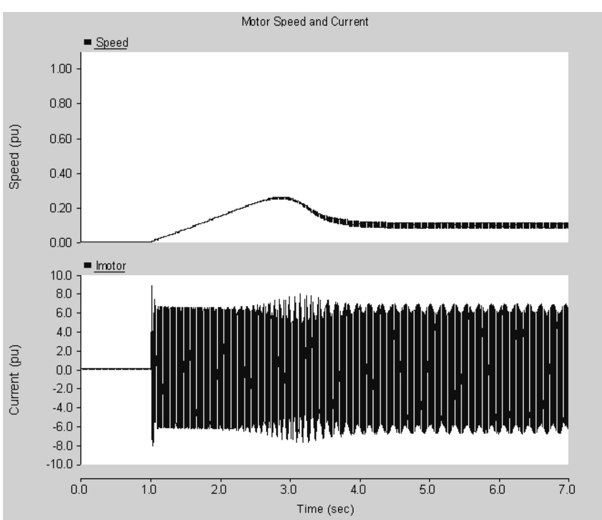

Fig. 12. Motor starting speed and current for case 1

It can be seen on Fig. 12 that in this condition, the motor speed does not reach its nominal value and that the starting current remains high. This condition will cause the motor to stall.

The second simulation case will define the size of the damping resistor that will prevent the self-excitation phenomenon with the same condition as case #1. A 75 Ω damping resistor is connected in parallel with the series capacitor when the motor is started.

It can be seen on Fig. 13 that in this condition, with the inserted 75 Ω damping resistor, the motor starting sequence is completed correctly. It has also been verified that this size of resistor eliminates the phenomenon for the unloaded feeder condition.

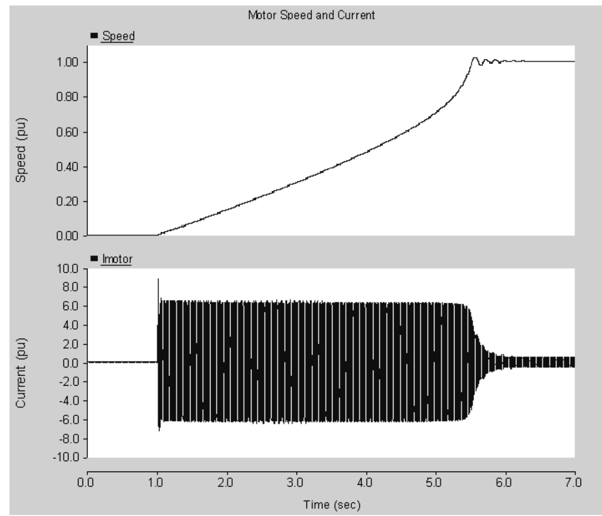

Fig. 13. Motor starting speed and current for case 2

The third case studied defines the minimum parallel load sufficient to avoid subsynchronous resonance without the need of inserting a damping resistor. It was found that a feeder current of approximately 85 A was adequate to achieve this condition. This value is used as an indication for the control system settings to automatically switch out the damping resistor when the feeder current reaches high enough levels.

It can be seen on Fig. 14 that for this case, the parallel load is sufficient to avoid the SSR phenomenon (the parallel damping resistor is not required). As in the previous case, the motor speed reaches its nominal value and the starting current is reduced to nominal once the starting sequence is completed.

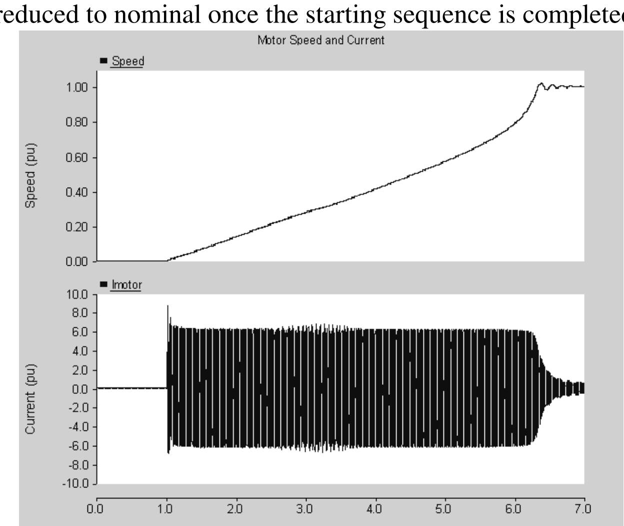

Figure 14. Motor starting speed and current for case 3

From these dynamic study cases, it is shown that a damping resistor of 75 Ω, which correspond to 10 times X_C, the capacitor bank impedance, is adequate to avoid SSR during motor starting for low feeder load conditions. Also, the control system will disconnect the damping resistor when the feeder current reaches 100 A for which the system damping is sufficient to avoid SSR. This will avoid unnecessary power losses during operation of the series capacitor.

VII. Conclusions

The use of the series capacitor for this 1750 hp motor in the Bassano service area and for the other existing installations is of great benefit to FortisAlberta. Series capacitors enable FortisAlberta to offer an inexpensive distribution wires solution to customers wishing to start large motors on distribution lines with low short circuit levels.

This avoids the great expense of installing a transmission substation at or near the customer's site. It also avoids the use of gas driven equipment that is more expensive than an electric drive motor. This saves the customer money and allows FortisAlberta to grow its distribution wires business.

For distribution series capacitor installations it is important to verify special conditions such as requirements for large motor starting in the initial planning stage of the project. Network simulations ensure that the proper protection and damping equipment is installed.

VIII. References

[1] S.A. Miske, "Considerations for the application of series capacitors to radial power distribution circuits" in *Power Engineering Society Summer Meeting, 2000. IEEE, Vol.4, Iss., 2000Pages:2607 vol. 4-*.

[2] IEEE Std 824-1994, "IEEE Standard for Series Capacitors in Power Systems"

[3] IEC 143-2 Part 2, "Protective equipment for series capacitor banks".

[4] C.F. Wagner, "Self-Excitation of Induction Motors with Series capacitors," AIEE Trans., 1941, pp.1241-1247

[5] 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 Operating Division, Vancouver, March 1995.

[6] N. Knudsen, "Two Characteristic Resonance Phenomena in Installations Containing Capacitance," ASEA Journal, 1954, ASEA Reg. 7339

[7] ASEA, "Series Capacitors for Distribution Networks, " ASEA Brochure No.7582E, 1961

IX. Biographies

David McCarrel, P. Eng., FortisAlberta graduated from the University of Waterloo, Canada with a Bachelor of Science degree in Electrical Engineering, in 1977.

His employment experience includes positions with Ontario Hydro, and Hydro Mississauga in Ontario, Canada. After moving out west, he has worked in Alberta, Canada for TransAlta, UtiliCorp Networks Canada, and he is currently with FortisAlberta. Mr. McCarrel has held various technical and supervisory positions, over his 28 years of experience in both the transmission and distribution areas of the utility industry. His present position is Supervisor, Distribution Planning, FortisAlberta and he is currently responsible for Distribution Planning for the FortisAlberta system.

Richard Bahry, P.Eng, FortisAlberta graduated from the University of Alberta, Canada with a Bachelor of Science degree in Electrical Engineering, in 1980.

His employment experience includes positions with Calgary Power, TransAlta Utilities, Utilicorp Networks Canada, Aquila Networks Canada and is currently with FortisAlberta. Mr Bahry has held various technical and supervisory positions, over his 25 years of experience in the power distribution area of the utility industry. He currently works in Distribution Planning and is responsible for determining electrical distribution system upgrades to accommodate requests for large load additions and distributed generation interconnections.

Mr. Bahry is an active participant on technical committees that develop Provincial and Federal Distributed Generation (DG) Interconnection Guidelines. He actively applies the technical guidelines to successfully connect large loads and to interconnect DG onto the distribution system.

Pierre Bérubé, ABB obtained his B.A.Sc. from University of Sherbrooke, QC, Canada in 1988. Since then he has worked for ABB Canada, with the Power Systems Division, where he has been involved in numerous transmission and distribution projects.

In particular, he was project and commissioning engineer for the Hydro-Québec 735 kV Series Capacitors project. He was also involved, more recently, in system studies for distribution series capacitor applications. His present position is Systems Engineer for the ABB Systems Division.

Anders Folkesson, ABB graduated from Chalmers University of Technology, Gothenburg, Sweden with a diploma of Master of Science in Electrical Engineering, in 1985. His employment experience includes various engineering positions with high voltage equipment for ABB in Sweden. After immigrating to Canada in 1998 he joined the Systems division within ABB Canada. His current position is Senior Project Engineer for ABB Systems Division.