Analysis of Temporary Over-Voltages from Self-Excited Large Induction Motors in the Presence of Resonance - Case Studies

T.G. Martinich, M. Nagpal, A. Bimbhra

Abstract**-- Technological advancements in high-power electronics for motor starting are enabling large squirrel cage induction motors to be connected to remote and weak parts of the power system. Sudden isolation of these motors, such as during line switching or fault clearing, does not mean that the rotor immediately stops turning and terminal voltages collapse. On the contrary, since both the motor and the driven mechanical load have rotational inertia, the rotor slows down over time. If the isolated high voltage system has sufficient capacitance to provide the magnetizing current of the motor, the air gap flux can be temporarily sustained or even grow for a while. This phenomenon is called self-excitation. The motor itself can act as a self-excited induction generator and temporarily supply energy to the network while the kinetic energy of rotation is converted to electrical energy as the motors slow down. The overvoltages arising from these temporary sources can be greatly exacerbated by resonance. As seen from the motor terminals, if there is a low-loss series resonance with the resonant frequency near the fundamental frequency, a dynamic overvoltage results. Overvoltages in the isolated subnetwork that would ordinarily not be of much concern can actually grow very quickly and become greatly amplified. In extreme cases, the dynamic overvoltages after isolation can be hazardous. This paper presents a simplified linear network analysis approach that can be utilized to quickly and efficiently identify conditions where self-excitation and resonant overvoltage problems can be expected when a customer proposes to connect motors to the network. To demonstrate the application of the method, two actual case studies will be presented which provide an insight into the phenomenon of self-excitation of induction motors with voltage amplification due to series resonance. A solution is discussed which was recommended and adopted for these two customers.**

Keywords**: Self-Excitation, Induction Motor, Temporary Over-Voltages, Resonance, Transients Studies, System Protection.**

I. INTRODUCTION

Technological advancements in high-power electronic drives for motor starting are enabling industrial customers to connect squirrel-cage induction motors, which can have power ratings in some cases of many thousands of kW, to remote and weak parts of the power system. Variable speed drives (VFDs) are an example of this technology. Customers in the oil, gas and the mining industries typically have large electrical power requirements to operate large motors and are often located in areas that are remote from generating sources, where fault levels are low. Oil and gas producers frequently require electrical supply from the utility to run relatively large compressor motors to move product through pipelines over long distances from the oil and gas fields. The mining industry employs large motors in the extraction and grinding processes which must be supplied from the grid to be economically feasible. Transmission customers supplied from a single circuit can become abruptly isolated from the grid for various reasons, including line tripping to clear faults, unintended opening of line terminal breakers, or protection misoperation. Overvoltage problems with the isolated system may arise when the customer has relatively large motors that isolate with a capacitive high voltage (HV) system with or without power factor correction capacitor banks. Sudden isolation of these motors with part of the transmission system does not mean that the rotor immediately stops turning and terminal voltages collapse. On the contrary, both the rotor and the driven mechanical load have rotational inertia which allows them to continue rotating for some time while they coast down to standstill as their rotational energy is consumed. Flux linkages in the machines as well as the voltage across the shunt capacitance of the line cannot instantly collapse. Under certain conditions the magnetizing current for the still rotating machines can be supplied by the connected capacitances in the isolated subsystem. If the stator currents are now at leading power factor, the motors become self-excited and there can be a transition from induction motor to self-excited induction generator operation. Self-excitation has been discussed in several early technical papers [1, 2, 3]. Air-gap flux can be temporarily sustained or could even grow as the motors coast down to standstill. Uncontrollable machine terminal voltages may lead to dynamic overvoltages in the isolated system [4]. The over-voltages can be exacerbated when the inductance of the motor and leakage inductance of the interconnecting transformers together with the shunt capacitance of the isolated HV system and power factor correction form an equivalent L-C circuit having a series resonant frequency near

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fundamental frequency. Since motor slip is initially very small, the resonance can be excited by the air-gap voltage. The overvoltages are more severe when the residual connected load, such as small low voltage motors or residential loads, are too small to provide effective damping. Overvoltages in the isolated subnetwork that would not ordinarily be of much concern can actually grow very quickly and become greatly amplified by the resonance. In extreme cases, overvoltages after isolation can be hazardous while the large motors are backfeeding the subnetwork.

This paper presents a simplified linear network analysis approach that can be utilized to quickly and efficiently identify and understand the conditions where self-excitation and resonant overvoltage problems can be expected when a customer proposes to connect motors to the network. To demonstrate the application of the approach, two actual case studies will be presented which will provide an insight into the phenomenon of self-excitation of induction motors when they become isolated from their regulating source in combination with voltage amplification due to series resonance.

The first case study considers a customer operating a natural gas compressor station who proposed to connect his relatively large induction motors to a long 144kV transmission line already supplying an existing small customer. The linear network analysis approach is compared to the results obtained using an electromagnetic transients program where the network is modeled in detail together with the classical electro-dynamic model for the induction motors, with the option of including nonlinear effects of saturation and surge arresters. The comparison verifies the simplified approach and in fact was confirmed by the customer's consultant using a different electromagnetic transients program. The second case also involves a customer proposing to tap a gas compressor station into a long transmission line. The system impact study for this customer takes advantage of the experience gained from the previous one, demonstrating that the simplified linear network approach is an adequate analysis approach to quickly verify if there are any over-voltage issues to be expected. For this case, the system was modeled in detail in an electromagnetic transients program although the induction motor model was simpler. Validation of the results was also done independently by the customer's consultant. The solution adopted to mitigate or safeguard the system against self-excitation and voltage amplification during temporary motor backfeed is discussed.

II. CASE 1

A. Background

An industrial customer proposes to connect an 8.6 MVA natural gas compressor plant to a 208 km 144 kV circuit using a 10 km tap circuit. A small industrial customer is already supplied by this same circuit. The 144 kV line connects a 45 MW gas turbine-generator station to the grid and forms part of a radial system from the grid to a 144kV/25kV distribution substation. The positive sequence capacitive line-charging is approximately 16 MVAR. Figure 1 shows a simplified electrical single-line diagram (SLD) of the system. Station R denotes the main 144 kV bus at the grid, Station F denotes the generating station and Station W denotes the 144/25 kV distribution station at the remote end of the radial system. The large industrial customer is referred to as Customer H while the small customer is Customer K. The gas compressor plant would include six 800 HP and three 1750 HP squirrel-cage induction motors supplied from a 4.16 kV bus plus a number of small low voltage motors and auxiliary loads. The customer intends to start each of the large motors by a variable speed drive. Once started, the motor will be switched onto the AC bus. The shunt capacitors on the 4 kV bus are for power factor correction. The utility intertie transformers at both customers have delta-connected HV windings. The neutral grounding for the 144 kV system is provided at the line terminal Stations R, F and W. Hence, opening of the 208 km line at Stations R and F creates an isolated and ungrounded 144 kV system having two connected industrial customers. The combination of 16 MVAR of shunt capacitance of the long line together with large induction motors, which can temporarily act as induction generators, introduces a concern of self-excitation and dynamic over-voltages as discussed in the following section.

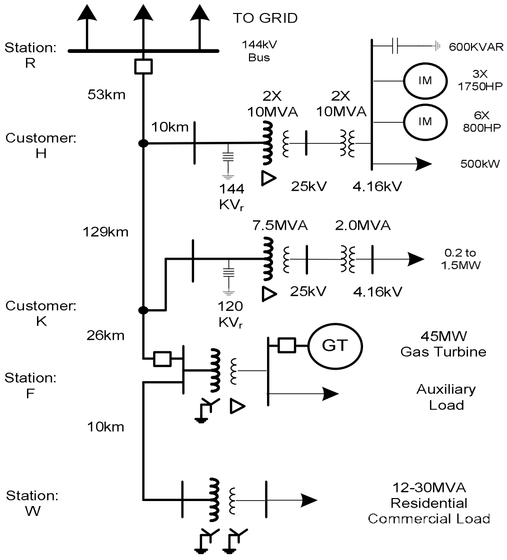

Figure 1: Simplified Single-Line Diagram of the 144kV System with small industrial Customer K and Customer H having over 10,000 HP of large induction motors.

B. Simplified Approach to Analysis of Self-Excitation when Customer's Motors Backfeed the Isolated Line

The customer's motors can temporarily backfeed into the 144 kV line for a variety of reasons, such as during the clearing of line faults, inadvertent opening by operating personnel or by protection misoperation when one terminal is already open for some reason. To assess the severity of the overvoltages resulting when the motors temporarily backfeed into the transmission line, it is instructive to employ a simplified analysis approach using sequence circuits [5]. Consider the clearing of a single line-to-ground (SLG) line fault. Figure 2 shows the interconnection of the positive, the negative, and the zero sequence equivalent circuits for the case where the line terminal breakers have opened to clear a sustained SLG fault on the 208 km line. The customer's motors have been assumed to become isolated with the faulted line. The positive sequence line charging capacitance is 2.0µF and the zero sequence capacitance is 1.2µF.

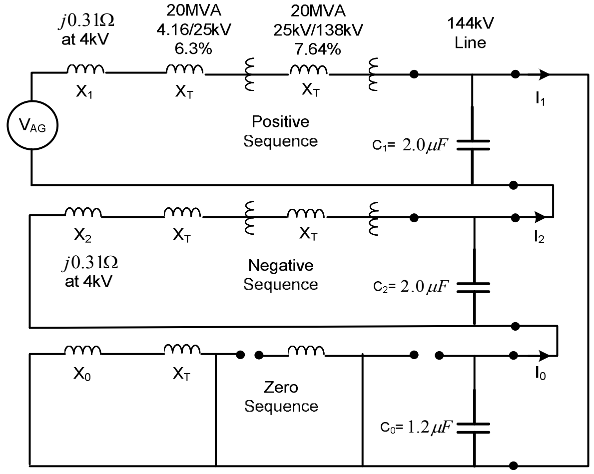

Figure 2: Connection of sequence networks to represent a permanent SLG fault on isolated 208 km 144kV line with customer motors still connected.

The operational impedance of the motor is the locked rotor impedance for fault analysis [6]. In the zero sequence circuit, the HV delta windings of the intertie transformer isolate the motors from the system. The nonlinear effects of surge arrester operation, corona and machine and transformer saturation have been neglected. The damping effects of Customer K have also been ignored as its load is assumed to be small. For simplicity, the line charging capacitance is assumed to be a lumped shunt capacitance at the customer's HV terminals.

The sequence networks can be reduced to a sinusoidal voltage source behind the simple circuit shown in Figure 3. Since slip is very small for large squirrel-cage induction motors, the frequency of the isolated system, determined by the motors, is near fundamental frequency for this linear network analysis. The driving point impedance versus frequency scan of this circuit, also shown in Figure 3, exhibits a series resonance at 68 Hz. The proximity of this resonance to fundamental frequency plus the relatively large shunt capacitance of the circuit leads to the expectation of a dynamic overvoltage problem when the motors temporarily backfeed the 144 kV line having a sustained SLG fault.

Reference [4] provides analysis of two additional cases when the motors backfeed into the 144 kV line: (1) during clearing of a sustained phase-to-phase fault and (2) following abrupt isolation for no fault. Simple linear network analysis predicts that no overvoltage problem is expected for the fault but there would be a problem for abrupt isolation for no fault. This was confirmed by the electromagnetic transients simulations.

C. Simulation of Case-1 with an SLG Fault using an Electromagnetic Transients Program

The system shown in Figure 1 was modelled in an electromagnetic transients program. The squirrel-cage induction motors were modeled as classical electro-dynamic machine models. Mechanical load torque was assumed to remain constant during the simulation. It should be noted that the surge arresters at the customer 144 kV entrance have a voltage rating of 144 kV for Customer H and 120 kV for Customer K. These arresters were also modelled. A sustained SLG fault on the line was simulated where the line terminal breakers opened, leaving the motors connected and backfeeding the isolated 144 kV subnetwork. A phase A-to-ground fault occurred on the line at time T=5.1 s and both line terminals opened within 12 cycles. Initially, nonlinear effects were omitted in order to demonstrate the basic effects of the resonance phenomenon.

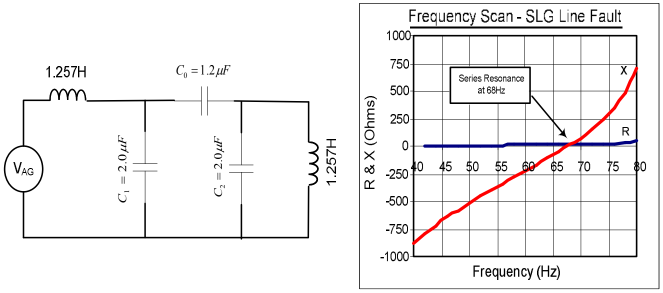

Figure 3: Reduced equivalent circuit for SLG fault of Figure2 and its impedance vs. frequency scan as seen from air-gap voltage.

Figure 4 shows the instantaneous phase-to-ground voltages at the 144 kV bus and the 4 kV motor terminals at Customer H. The voltage waveforms for Customer K (not shown) are similar. Note that, prior to fault application, the customer's voltages were about 1.0 pu.

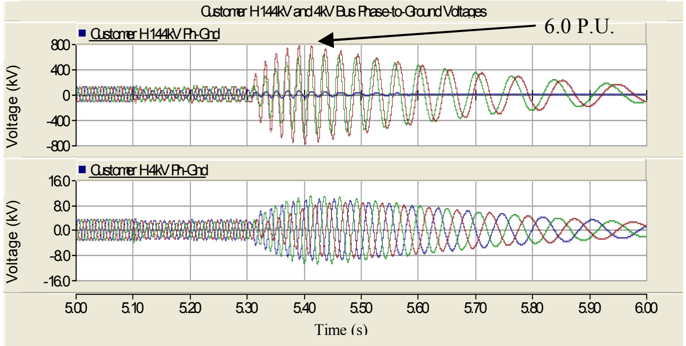

Figure 4: Simulation of Customer H bus voltages for a permanent SLG line fault with no surge arrestor or saturation included.

The voltage waveforms clearly demonstrate that, as soon as the faulted line with the motors connected isolate from their regulating source: (1) rotor speed and frequency start to decline and (2) voltages start to rise dramatically, reach a maximum about 6 cycles later, and subsequently decline. In an ungrounded system, grounding one phase causes a "neutral shift" and the phase-to-ground voltages on the two unfaulted phases normally increase in magnitude to √3 pu. However, due to the proximity of a series resonance near fundamental frequency, the overvoltages are greatly amplified, as predicted by the analysis using simple sequence circuits showing the near fundamental frequency series resonance.

The previous simulation was repeated but nonlinear effects of saturation and surge arrester operation were included. Figure 5 shows the resulting instantaneous voltages at Customer H 144 kV and 4 kV busses for the same sequence of fault application and line terminal opening as before. Comparison of these plots to Figure 4 demonstrates the limiting effects provided by surge arresters and magnetic saturation. The transient overvoltages appearing on the 144 kV bus are still relatively high, at 2.0 pu. The corresponding voltage waveforms for Customer K appear in Figure 6. The 4 kV bus at Customer K experiences a dynamic overvoltage of nearly 1.5 pu on the most affected phase. Figure 7 provides the surge arrester energy accumulation at the two customers. The figure shows that the 120 kV_r arrester on one of the unfaulted phases at Customer K absorbs more than 1.6 MJoule. This greatly exceeds the capability of a 7.1 kJ/kV_r arrester and would be expected to fail.

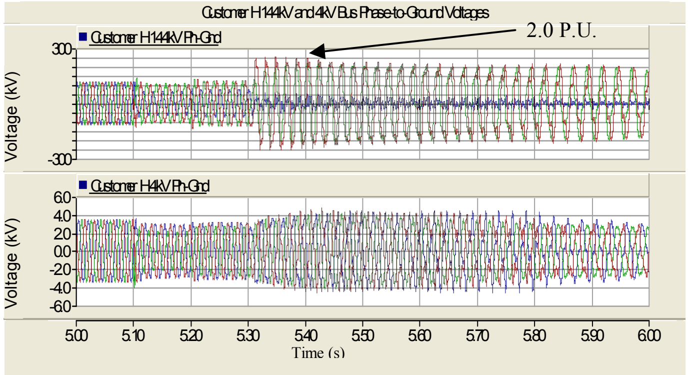

Figure 5: Simulation of Customer H bus voltages for a permanent SLG line fault with saturation and arrester conduction included.

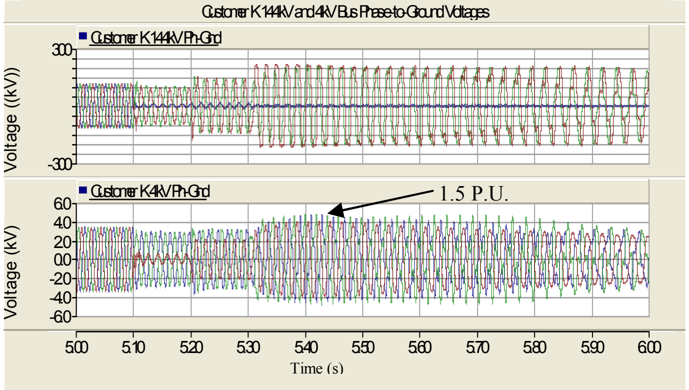

Figure 6: Simulation of Customer K bus voltages for a permanent SLG line fault with saturation and arrester conduction included.

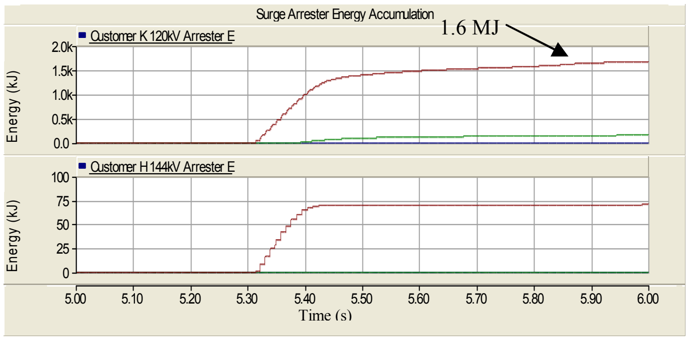

Figure 7: Simulation of surge arrestor energy accumulation at Customers H and K for a permanent SLG line fault.

The voltage waveforms are given in Reference [4] corresponding to the clearing of a sustained line-to-line fault as well as abrupt opening of the line and isolation of the motors for no fault. No dynamic overvoltage occurs with the line-to-line fault whereas dynamic overvoltage occurs for abrupt opening where only the positive sequence network is involved. Both of these results were predicted by the simplified linear network analysis.

D. Discussion of Results for Case-1

The simplified linear network analysis approach using equivalent sequence networks leads to the expectation of dynamic overvoltage problems when the customer's motors are allowed to backfeed the isolated line having a sustained SLG fault. This was confirmed by the detailed electromagnetic transients program simulations. The simplified approach will now be applied to assess a second case for dynamic overvoltage problems.

III. CASE 2

A. Background

The second case also involves a customer with large induction motors for a gas compressor plant proposing a tapped connection to a long 138 kV transmission line. For this case, validation of the analytical results was also done independently by the customer's consultant using an electromagnetic transients program.

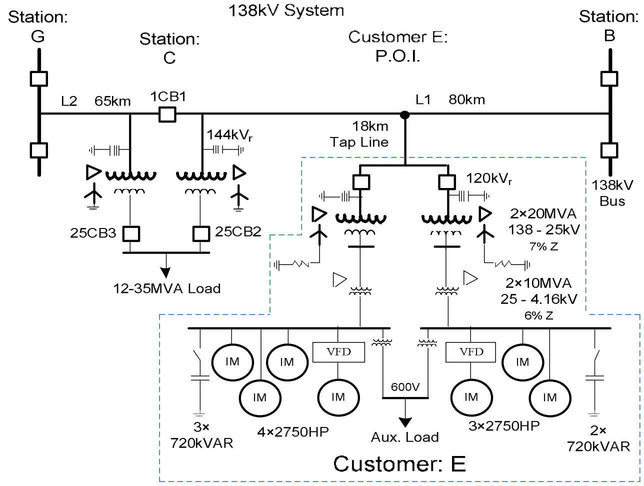

Figure 8: Simplified Single-Line Diagram of the 138kV System with Customer E having over 19,000 HP of large induction motors.

B. Description of Customer's Facilities and System

Figure 8 shows a simplified electrical SLD of the gas compressor plant and the portion of the utility 138 kV system to which it would connect, from station G via distribution station C to Station B. The 138 kV breaker at Station C sectionalizes the transmission system into two circuits; an 80 km circuit (L1) from B to C and a 65 km circuit (L2) from G to C. Station G is a major hydroelectric plant supplying a large 500 kV transmission grid as well as a meshed 138 kV network containing the subsystem shown in the SLD. The customer proposes to tap into the 80 km line with an 18 km tap line. There will be two 20 MVA 138/25 kV utility intertie transformers and two 10 MVA 25/4.16 kV transformers to supply the main motor load. The 25 kV and 4 kV bus tie breakers are normally open. There will be a total of seven 2.05 MW (2750 HP) squirrel-cage induction motors, four of which would be supplied from one 4 kV bus and the remaining three from the other bus. Two out of the seven motors can be supplied continuously from VFDs. Motors that are directly connected to the AC bus will be operating at full load while those supplied from a VFD can be operated from very light to heavy loading. There are switchable capacitor banks on each 4 kV bus to maintain a minimum overall power factor. Total positive sequence charging capacitance of L1, including the tap line, is about 6.5 MVAR and 4.3 MVAR for the shorter line L2. The 138 kV windings of the transformers at Station C and at the customer are delta-connected. Neutral grounding is provided by the transformers at Stations G and B. The surge arresters at Customer E will have a voltage rating of 120 kV whereas the arresters at Station C are rated 144 kV. As can be seen from the Figure, opening the 138 kV terminals of L1 during the clearing of line faults results in an ungrounded and capacitive HV subsystem which would be temporarily backfed from the motors. Failure of the 138 kV breaker at Station C to open results in the motors isolating with and backfeeding a significantly longer transmission system. Note that, for this contingency, both 25 kV breakers at the distribution station would be opened by line and breaker-failure protections, leaving almost no connected load to provide damping of transient and dynamic overvoltages.

C. Motor Backfeed during Clearing of SLG Faults

Consider the case when only one motor is in service and connected to the AC bus. (Any motor on a VFD is neglected for the analysis since the drive prevents the motor from backfeeding). It is reasonable to assume that no power factor correction is required to be on. The interconnected sequence circuits shown in Figure 2 for Case 1 are directly applicable here since the topology is the same. Only the values of the inductive and capacitive components need to be changed. For the single motor case, the air-gap voltage is effectively behind the series connection of the operational impedance of the motor, one 10 MVA transformer and one 20 MVA transformer. The leakage impedance of the 138/25 kV transformer is 7.0% (j2.188 Ω on 25 kV) and 6.0% (j0.1038 Ω on 4.16 kV) for the smaller transformer. The locked-rotor impedance of the 2750 HP induction motors is 15% (j1.035 Ω at 4.16 kV). The positive sequence capacitance of line L1 and 18 km tap line is 0.9 µF and the zero sequence capacitance is 0.476 µF. Inserting this data into the equivalent sequence circuits, the resulting circuit can be reduced to that shown in Figure 9. The driving point impedance versus frequency scan of this circuit exhibits a series resonance at a frequency of about 62 Hz.

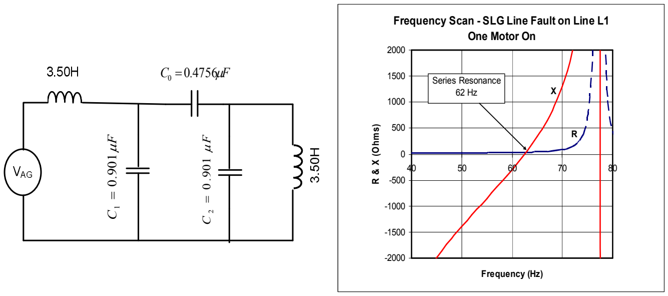

Figure 9: Reduced equivalent circuit for SLG line fault and one motor at Customer E isolating with circuit 1L358.

With series resonance so close to fundamental frequency, the relatively large capacitance of the isolated system, and so little residual passive load, the simplified analysis approach leads to the expectation of high dynamic overvoltages when one motor temporarily backfeeds into the isolated and faulted L1.

Figure 10 provides the results of an electromagnetic transients program simulation of the normal clearing of a permanent SLG fault on line L1 when one of the customer's motors is allowed to backfeed the line. For illustrative purposes, nonlinear effects of corona, surge arrester conduction and magnetic saturation have been neglected. As well, dynamics have not been included. A simplified approach was used for modeling the motors for the electromagnetics transients simulation. The large motors on each 4 kV bus were aggregated and collectively modeled as one equivalent machine with sinusoidal voltage sources behind the appropriate locked-rotor impedance. The instantaneous phase-to-ground voltages at Customer E 138 kV and 4 kV buses are shown in Figure 10. An SLG fault occurs at T=20 ms and the breakers at Stations B and C have opened by about T=125 ms. All of the voltages exhibit a dramatic escalation in magnitude as soon as the motors isolate with the faulted line. If the 138 kV voltages are inspected, one can see that (1) the escalation in the voltages of the unfaulted phases goes far beyond √3 pu expected from neutral shift in an ungrounded HV subsystem having an SLG fault, and (2) the waveforms are almost precisely in phase after isolation occurs and the motor backfeeds into the line. The latter observation indicates that a large voltage buildup develops across the zero sequence shunt capacitance of the line, as is easily verified by analysis using the sequence circuits.

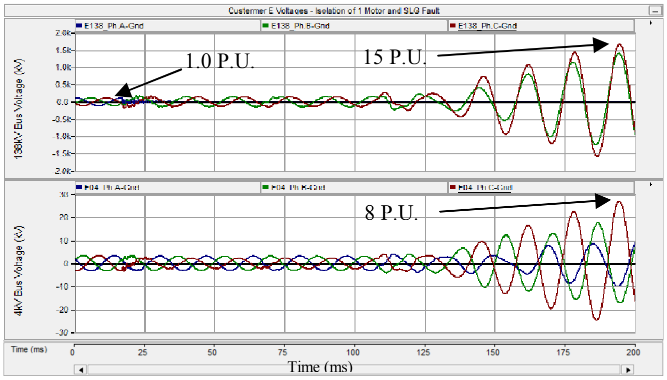

Figure 10: Simulation of Customer E 138kV bus (upper graph) and 4kV bus voltages when one motor isolates with L1 circuit and sustained SLG line fault. Saturation effects and surge arrester conduction are not included.

The previous study was repeated where surge arrester models were added at the customer and at Station C. The voltage waveforms at the customer appear in Figure 11 and the arrester energy accumulation in the customer's 120 kV_r arresters appear in Figure 12. The simulation shows the clearing of a sustained SLG fault on L1 when Customer E has only a single motor on the AC bus. Once the breakers open to clear the fault, the TOV on the 138 kV unfaulted phases, shown in the upper graph, is limited by the customer's arresters to about 1.8 pu (1.0 pu = 112.7kV_p). On the customer's 600 V bus (not shown) there is a one-cycle overvoltage of 1.9 pu and a subsequent TOV of about 1.7 pu. The two sets of 120kV$_r$ surge arresters on the most affected phase absorb rated energy (7.2kJ/kVr) within 12 cycles after motor backfeeding commences, which can be considered to be excessive energy accumulation.

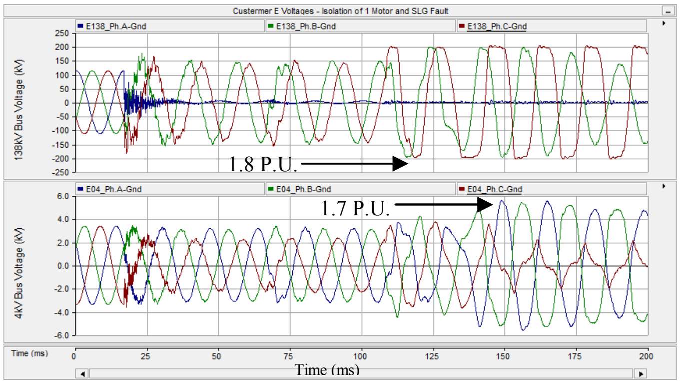

Figure 11: Simulation of the same motor backfeed scenario as for the previous case but surge arrester conduction has been included.

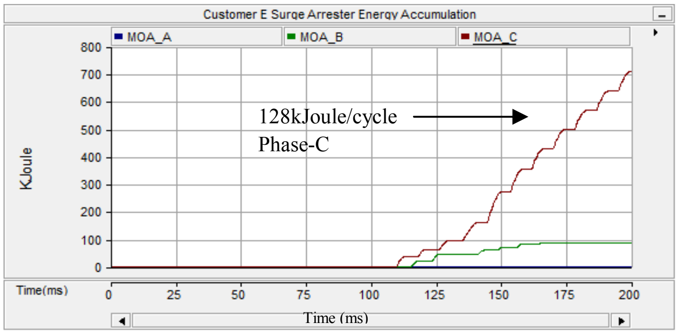

Figure 12: Simulation of energy accumulation in the customer's two 120kVr surge arresters during the motor backfeed condition.

Consider, now, that two motors are in service, one on each of the two 4 kV busses. The resulting interconnection of equivalent sequence circuits reduces to the simple circuit shown in Figure 13. The driving point impedance versus frequency scan of this circuit shows that the series resonance, due to the smaller circuit inductance, has shifted to a frequency of 89 Hz. The frequency shift away from the fundamental leads to the expectation of significantly reduced dynamic and temporary overvoltages during fault clearing. Figure 14 provides the simulated voltage waveforms at Customer E for the same SLG fault application and clearing sequence as in the previous simulations. Nonlinear effects and motor dynamics have not been included. These waveforms, when compared to the ones in Fig. 10, clearly confirm that the overvoltages are greatly reduced by the addition of the second motor, as predicted by the simplified analysis approach.

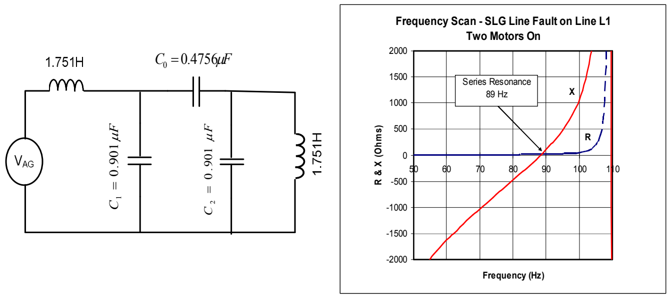

Figure 13: Reduced equivalent circuit for SLG line fault and two motors at Customer E isolating with circuit L1.

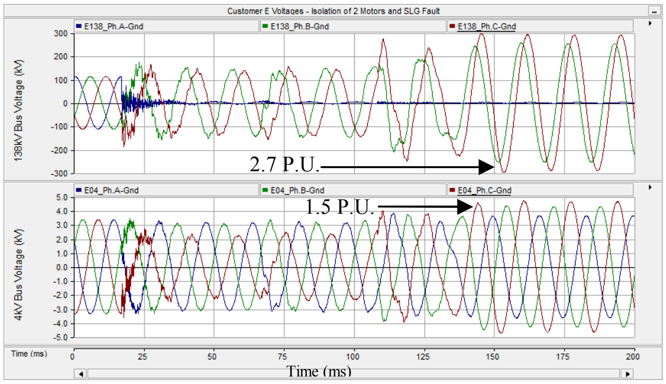

Figure 14: Simulation of Customer E 138kV and 4kV bus voltages when two motors isolate with circuit L1and sustained SLG fault. Saturation effects and surge arrester conduction are not included.

D. Motor Backfeed during Clearing of SLG Line Faults and Breaker Failure

Consider the case where two motors are directly connected to their independent AC busses. A sustained SLG fault is assumed to occur on circuit L1, the line terminal at Station B opens normally and at Substation C the 25 kV breaker in the line protection zone opens but the 138 kV bus tie breaker is stuck closed. In practice, breaker failure protection at the station will open the second 25 kV breaker to disconnect the station load and will send a direct transfer trip (DTT) to open the L2 line terminal at Station G. Once the line terminals at G and B have opened, the customer's motors will be temporarily backfeeding an isolated and "floating" 163 km 138 kV system having a C_1 of 1.50μF and a C_0 of 0.81μF. The equivalent source impedance is the same as the one appearing in Figure 13 for two motors.

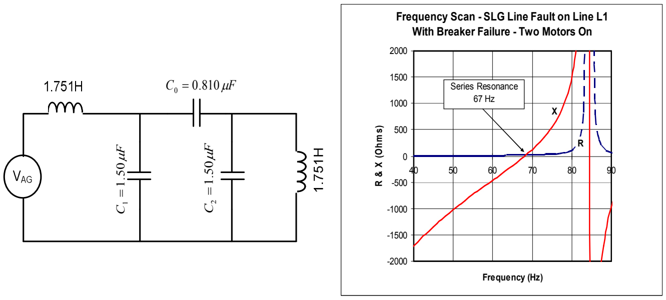

Figure 15: Breaker Failure Case: Reduced equivalent circuit for SLG line fault and two motors at Customer E isolating with both circuits L1 and L2.

The interconnection of the sequence circuits is now extended to include the breaker failure case. This is done by simply changing the values for C_0 and C_1 to obtain the circuit shown in Figure 15. The driving point impedance as seen by the air-gap voltage has a series resonance at a frequency of 67 Hz, indicating that an overvoltage problem is likely. This is confirmed by the simulation of Figure 16 showing rapidly escalating voltages after the motors isolate with L1 and L2 at T = 200ms. The 138kV line-to-ground voltages (upper graph) are far higher than √3 pu due to voltage amplification and resonance. Nonlinear effects have not been modeled in the simulation. It is interesting to note that, with two motors connected, there was only a moderate TOV when the customer isolated with 98 km of 138 kV line (L1 plus the 18 km tap line) having an SLG fault. However, when the same motors isolated with 163 km of line the TOV increased dramatically as the resonant frequency approaches the fundamental frequency, as seen by the simplified analysis approach.

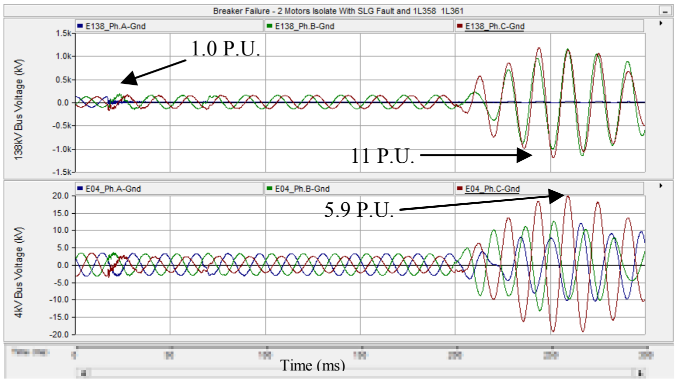

Figure 16: Breaker Failure Case: Simulation of Customer E bus voltages when 2 motors isolate with both circuits L1 and L2 and a sustained SLG fault. Saturation effects and surge arrester conduction are not modeled.

E. Discussion of Results for Case 2

The analysis of Case 2 has taken advantage of the experience gained from studying Case 1, demonstrating that a simplified linear network analysis can identify when overvoltage issues are to be expected. Section III has explored the following effects on the self-excitation and voltage amplification caused by changes in the location of the resonant frequency:

a) Changing the equivalent source impedance (number of motors) for a particular shunt capacitance of the isolated HV subnetwork (length of transmission line), and
b) Changing the line length for the same number of motors.

The expectation of obtaining high overvoltages during motor backfeeding situations revealed by the simple analysis was confirmed by electromagnetic transients simulation, including simulations performed independently by the customer's consultant. The solution recommended by the utility is discussed in Section IV, below.

IV. PREVENTING SELF-EXCITATION AND HIGH DYNAMIC OVERVOLTAGES

For customers who are tapped into a transmission system, the HV windings of their intertie transformer(s) will be ungrounded because it prevents de-sensitization of the utility's line protection. With an HV delta connection, the customer does not contribute fault current for SLG faults on the transmission system. Hence, the customer cannot detect immediately that such a line fault has occurred. If that was possible, it could be used as a signal to trip either the main entrance breaker or the motors at about the same time as the remote utility line terminals are being opened.

One solution to prevent overvoltages due to temporary motor backfeed is to install a high reliability tele-protection system from the line terminal stations to the customer to enable a direct transfer trip (DTT) signal to be sent to open the entrance breaker before the last line terminal opens. This may require delaying the opening of the line terminal breakers by a few cycles in order to ensure that the motor load has been disconnected first. Initiation of the DTT can be from line protection and/or from any non-protective trip to the line breakers. This solution was implemented for the customer considered in Case 1. It is also the recommended primary solution for Case 2. Other alternatives were considered but rejected because of either technical reasons or excessive cost.

V. CONCLUSIONS

Large induction motors, when they isolate from their regulating AC supply and form part of a capacitive subnetwork, can become self-excited induction generators if the air-gap flux is temporarily sustained. As rotor speed declines towards standstill, kinetic energy of rotation is converted to electrical energy. Voltage amplification can occur if the equivalent network, as seen by the air-gap voltage, has a series resonance near fundamental frequency. If the residual load in the subnetwork is low, dynamic overvoltages can become high enough to be hazardous.

This paper has demonstrated that a simplified linear network analysis approach is a useful tool that can be utilized to quickly and efficiently identify conditions where self-excitation and resonant overvoltage problems can be expected during motor backfeed. Two actual case studies of motor isolation with a capacitive subnetwork, leading to high dynamic overvoltages have been presented to demonstrate the application of the analysis approach. This method was compared to the results obtained using an electromagnetic transients program with a detailed network model together with either a classical electro-dynamic model or a simplified model of the induction motors. Comparison verified the conclusions obtained with the simplified approach and, in fact was further confirmed in both cases by the customer's consultant using a different electromagnetic transients program than the one used by the authors. The solution that was implemented for Customer H and recommended for Customer E was the installation of a highly reliable tele-protection scheme with delayed opening at the line terminals. This solution at Customer H has been in service for more than two years.

VI. REFERENCES

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