SIMULATION STUDY OF A DYNAMIC VAR COMPENSATOR AS A SOLUTION TO A LARGE MOTOR START PROBLEM

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ABSTRACT

Starting of large motors presents significant challenges, especially on weaker power systems. This paper describes a simulation study to quantify the impact of starting of proposed new large motor load on a specific high-impedance feeder, and the use of a dynamic VAr compensator to mitigate the adverse motor start impacts. The results show a) the value of transient simulation in applications of this type; and b) the effectiveness of the dynamic VAr compensator as a solution to this problem.

I. NOMENCLATURE

DVC	Dynamic VAr Compensator
FIDVR	Fault-Induced Delayed Voltage Recovery
NPPT	Northern Plains Power Technologies
RVAT	Reduced Voltage Auto-Transformer
SSI	Switched Starting Impedance
SSVR	Solid State Voltage Reducer

II. INTRODUCTION

MANY industrial customers have loads that include large motors, in some cases into the thousands of horsepower. Starting of such large motors is well known to be challenging, particularly on higher-impedance systems [1,2]. To prevent motor starts from causing voltage problems for other customers on the feeder, and to ensure reliable starts of the motors, soft-starters of various types, such as switched starting impedances (SSIs), Reduced Voltage Auto Transformers (RVATs), Solid State Voltage Reducers (SSVRs), six- or twelve-pulse rectifiers, or Variable Speed Drives (VSDs) are employed [3, 4]. However, if the motors are sufficiently large or the source impedance sufficiently high, even soft starters may not be enough to completely mitigate the negative impacts of motor starts.

In the case considered in this paper, an industrial customer wishes to connect a new facility that will be fed at 69 kV by a feeder that is roughly 84 miles long. The impedance of that 69 kV feeder is quite high. The new customer site will consist primarily of large motor loads driving pumps or compressors. Many of these new motors are well into the thousands of horsepower, and this combination of a high impedance feeder and such large motors could be expected to cause difficulty. Also, this 69 kV feeder feeds a 69 to 24.9 kV substation serving other customers, and the local utility must be concerned about the impact of the proposed new motor load on the power quality on those customers. To mitigate the expected problems, the utility has proposed adding a Dynamic VAr Compensator (DVC) [5] at the proposed new load site. A simplified block diagram of the DVC system is shown in Figure 1. The center of the system is a DC-AC converter with its DC voltage supported by a rather large DC capacitor. The DC side voltage is controlled by the converter via a small amount of real power (P) drawn by the converter from the grid and fed to the capacitor. On the AC side, the converter's controls monitor the AC side voltage and use that in closed-loop mode to determine the appropriate amount of reactive power (Q) to source back to the grid. A DVC has the advantages of being able to supply voltage support much more quickly than an electromechanical voltage regulator, and to vary its output continuously, not in a discretized way. The DVC's control range (how far it can swing the voltage via its Q output), depends on the system impedances. To extend the range of the DVC system, additional AC side switched capacitors are included as shown by the dashed box in Figure 1. These capacitors are controlled by the DVC logic.

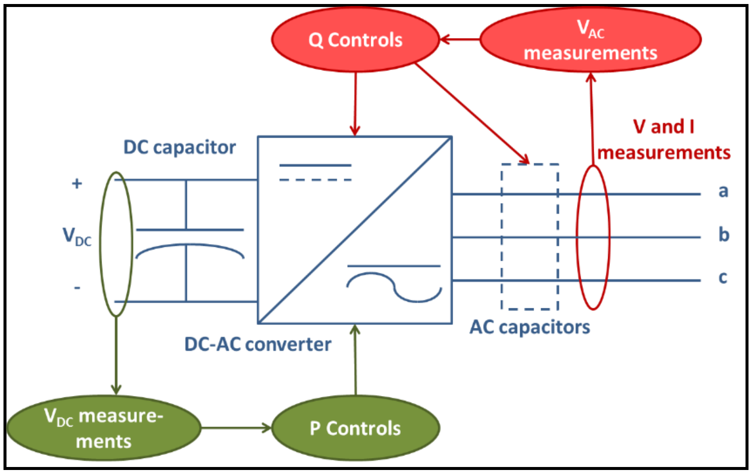

Figure 1. Simplified block diagram of the DVC.

In this paper, the problem posed by the large motor starts, the ability of the DVC to mitigate that problem, and additional implementation recommendations, are quantified via transient simulation.

III. Procedure and Methodology

A. Feeder modeling

The feeder and load were modeled in detail using data provided by the utility and the customer. A schematic of the model is shown in Figure 2, and a zoomed view of the new customer site interconnection is shown in Figure 3. The 69 kV source is represented by a Thevenin equivalent. For most of the work reported here, the 69 kV source was set to 105% of its nominal value, which is the typical setting for the non-automatic tap changer on the 230:69 kV transformer at the head end of the 69 kV line. The 69 kV circuit is tapped in five locations. Each of the five feeder sections along with their loads are represented using data provided by the utility. The loads other than the new proposed motor load are represented as constant-impedance loads, with one exception: one of the upstream sites was found to contain four 575-hp induction motors driving pumps, and to capture their contribution to any FIDVR-like effects, these motors were modeled explicitly. The local 69:24.9 kV substation and its feeders are modeled in detail based on the data provided by the utility. The substation contains a single 69:24.9 kV 10 MVA transformer with an X/R ratio of 10 and an impedance of 8.2%. There are two capacitors on the 24.9 kV system, both of which are included in the model. The proposed new motor load is fed from the substation 69 kV bus via a ≈ 3000 ft long 69 kV spur that will connect to a pair of 69:4.16 kV step-down transformers at the customer site. In Figure , the green block is the substation's 69:25 kV transformer. The right-hand side of the transformer is the 69 kV side, and the left-hand side and the feeder segments extending away from there are the 25 kV side. It can be seen in Figure 3 that the new customer site ties in on the 69 kV side, through an impedance that represents the new 69 kV spur. Figure also shows the DVC's external capacitors and their relaying (lower right of the figure). Note that the DVC is connected to the existing 24.9 kV bus, not the new 69-kV spur.

B. Load and soft starter modeling

The only motor loads whose startup characteristics and impacts are to be studied are those at the new customer site. All other customer loads will be considered to be either on and in steady state, or off, when the customer's motors are

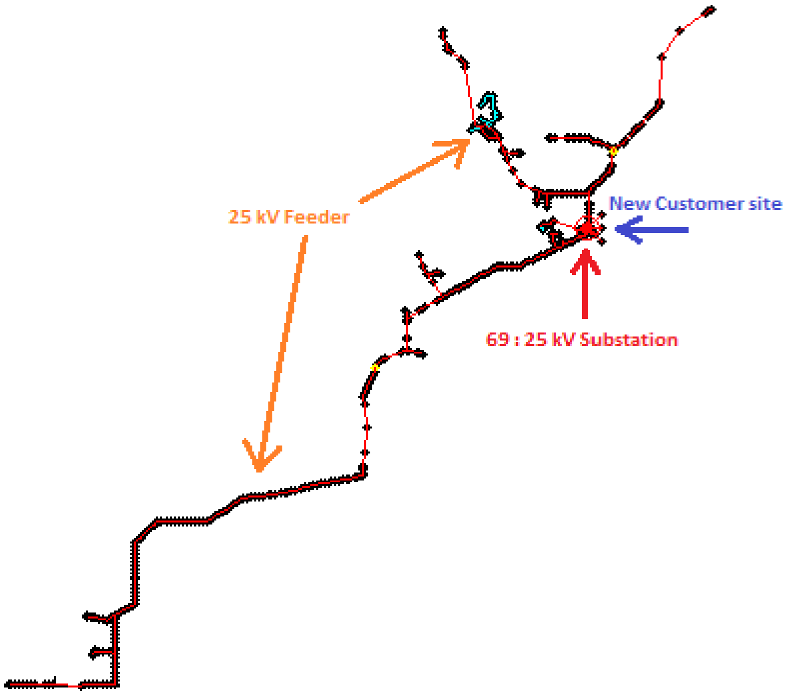

Figure 2. Schematic of the entire model of the local substation, its 25 kV feeders, and the new customer site.

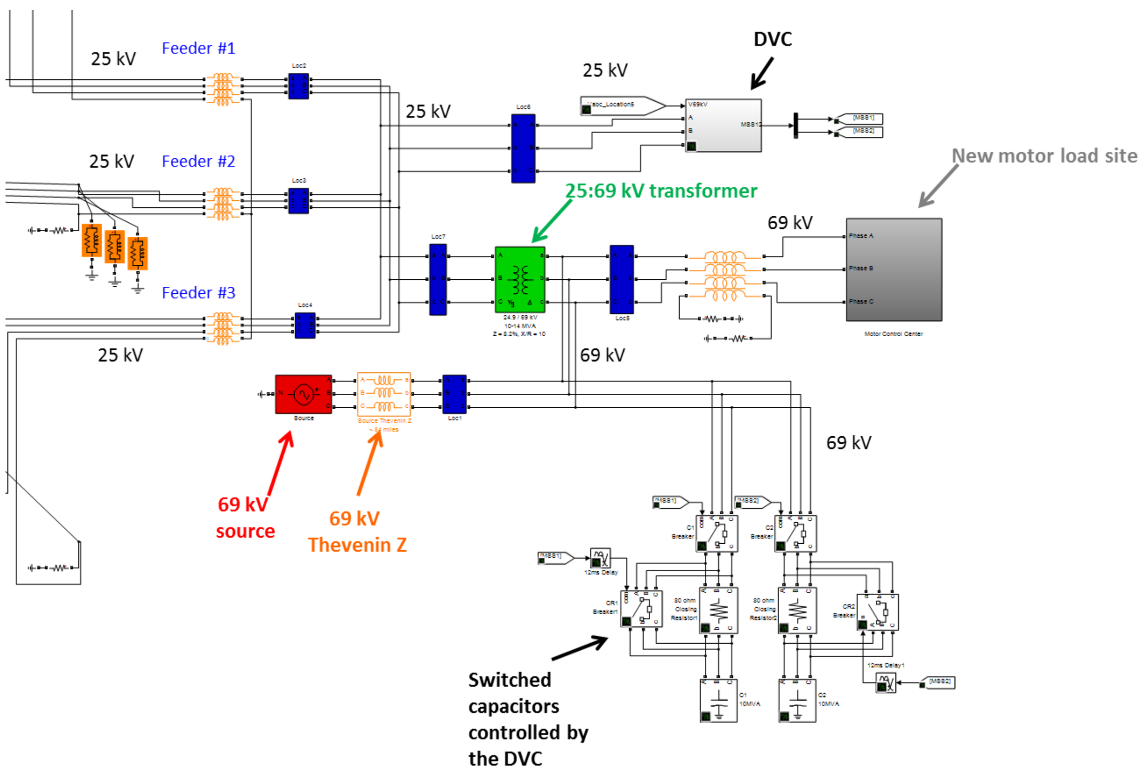

Figure 3. Zoomed version of Figure 2, showing the local substation, DVC, and the new customer site.

switched. Thus, the other customer loads are modeled either as impedance loads or constant-power loads as appropriate. Based on information supplied by the utility and the customer, the motor load at the new customer site was separated into four main classes:

- Three 4650 hp (3.5 MW) brushless synchronous motors driving compressors, supplied via RVATs.
- One 2200 hp (1.6 MW) brushless synchronous motor driving a compressor, supplied via an RVAT.
- Four 1500 hp (1.1 MW) induction motors driving pumps, supplied via SSVRs.
- Two 800 hp (0.6 MW) induction motor driving compressors, started directly across the line.

The induction motors are started under load. The synchronous motors have their mechanical loads applied to them at 95% speed by a clutch that is modeled by ramping the load torque from zero to the correct T_{mech} for the given speed over a period of one second. The motors themselves were modeled using MATLAB/Simulink's built-in models, with parameter values supplied by the manufacturers. Based on consultation with the manufacturer, the synchronous machines were modeled using MATLAB's sixth-order synchronous machine model with a fixed field voltage that is applied when the motor reaches 95% of synchronous speed. According to information supplied by the customer, in these synchronous motors the field voltage is held to zero until the motor reaches 95% of rated speed, so that the motor starts as an induction machine [6]. At 95% speed, the field voltage is switched to a user-settable value that is chosen to achieve a power factor of 0.99 lagging. The induction machines used the built-in sixth-order induction machine model in MATLAB.

Because this study is primarily concerned with motor start impacts, it was important to model the soft starters in detail. The RVAT is a three-winding autotransformer that is used to decrease the applied motor voltage during startup. From zero speed up to a user-selected speed threshold S_1, the autotransformer applies 50% of the grid voltage to the motor terminals. Once S_1 is reached, the RVAT switches in a second transformer winding, and 65% of the grid voltage is applied to the motor terminals, until a second threshold S_2 is reached. At S_2, the autotransformer is switched out (bypassed) and the full grid voltage is applied to the motor. NPPT was not given values for S_1 and S_2, so as a starting point for this work, the values used for S_1 and S_2 in units of per-unit speed are $S_1 = 0.5$ and $S_2 = 0.65$ [3]. Also, NPPT was not provided with impedance values for the RVAT autotransformer, so standard impedances (5.75%, X/R = 10) were used, and transformer MVA ratings were chosen based on the motor size. In this application, RVATs are only used with brushless synchronous motors. In motors of this type, the operating power factor of the motor can be adjusted by changing the field current [7].

The SSVR uses a three-phase set of triacs that reduces the applied motor voltage by "chopping" it in the same manner as in an incandescent lamp dimmer. The SSVR applies a set of voltage steps to the motor to bring it up to speed, and then is bypassed at 95% of rated speed. The voltage steps are as follows: the firing angle is 80% for 0.5 sec; then 75% for 1 sec; then 70% for 2 sec; then 65% for 11.5 sec, recalling that a larger firing angle means that a smaller RMS voltage is being applied to the load. These steps sum up to 15 sec. At 15 sec, the firing angle goes to 60% and holds there until the SSVR is bypassed. The reason for this is that the startup current of the 1500 hp induction machine has so much phase shift that the applied voltage for a firing angle of 60% is very nearly 1 pu (the phase-shifted current does not let the first SCR in the triac turn off before the next triac fires) [8].

C. DVC modeling

A high-level block diagram of the 8 MVAr DVC model is shown in Figure 1 above. The DVC was modeled in detail using information from the manufacturer, coupled with the experience and prior knowledge of NPPT investigators. An averaged model of the inverter is used, and the interface transformer is explicitly modeled. The inverter controls and DVC overcurrent protection are modeled in detail. Some controller details were provided by the manufacturer, but many of the lower-level details of the DVC, such as the output filter configurations and certain details of the line synchronization method (PLL) and current regulator, were not shared due to confidentiality concerns. However, transient test data were supplied, and with these data and consultations with the DVC manufacturer, NPPT investigators designed a controller and filter and then tuned the controller so that the model matched the experimental results. The result is a DVC model that is necessarily somewhat approximate, but that should be behaviorally very similar to the actual unit in all important respects and is trustworthy for present purposes.

D. Simulation plan

The goal of the simulations was to gain understanding of how effectively the DVC will mitigate the impacts of the new customer's motor starts on the feeder voltage, as well as to probe the characteristics of the system more generally when the DVC is used in this way. The plan was to bound the solution space by simulating the worst-case scenarios. Under the operating rules for the new site, the large motors will always be started one at a time, so it was not necessary to test combination motor starts. Also, each motor in each class could be considered identical and interchangeable from a system perspective, so an individual start of only one type of each class needed to be simulated. Of the individual motor starts, the boundary cases should occur when each motor is started by itself (each motor is the first to start), or when each type of motor is started with all other motors already running (each motor is the last to start). This rationale resulted in 16 use cases, which are listed in Table 1 along with the results for each case.

Table 1. Brief summary of the results of the study.

Motor	Position in starting order	DVC on?	Result
800 hp	First	No	Start
800 hp	First	Yes	Start
800 hp	Last	No	Fail
800 hp	Last	Yes	Start
1500 hp	First	No	Start
1500 hp	First	Yes	Start
1500 hp	Last	No	Fail
1500 hp	Last	Yes	Start
2200 hp	First	No	Start
2200 hp	First	Yes	Start
2200 hp	Last	No	Fail
2200 hp	Last	Yes	Fail
2200 hp, adjusted RVAT	Last	No	Fail
2200 hp, adjusted RVAT	Last	Yes	Start
4650 hp	First	No	Start
4650 hp	First	Yes	Start
4650 hp	Last	No	Fail
4650 hp	Last	Yes	Fail
4650 hp, adjusted RVAT	Last	No	Fail
4650 hp, adjusted RVAT	Last	Yes	Start

IV. Results and Discussion

The results of the simulations can be summarized as follows.

Without the DVC: all of the motors were able to successfully start when they were the first one to start. For the last-motor starts without the DVC, none of the motor starts were successful. In all last-to-start cases, the motor being started failed to come up to full speed, and/or the motor start pulled the voltage down sufficiently that other motors began to stall (a FIDVR-like event).

With the DVC: the DVC improves the power quality for all motor starts. All motors successfully started in the first-to-start case. In the last-to-start case, all successfully started except two: the 2200 hp and the 4650 hp brushless synchronous machines on an RVAT, which failed to come up to full speed even with the DVC. The recommended mitigation strategy involves using the DVC *and* a change to the settings of the RVAT as explained below.

Four of the use cases explored are described in detail below as representative examples of the study's results.

A. 1500 hp motor start, last to start, without the DVC

The first case examined is the 1500 hp motor start in the last-to-start position, without the DVC. Figure 4 is a plot of the motor speeds, and Figure 5 shows the motor bus voltage and current. Figure 5 indicates that the motor bus voltage has been pulled down to just under 80% of nominal, and as a result, even the already-operating motors cannot maintain correct operation and begin to stall, as indicated by the speeds in Figure 4.

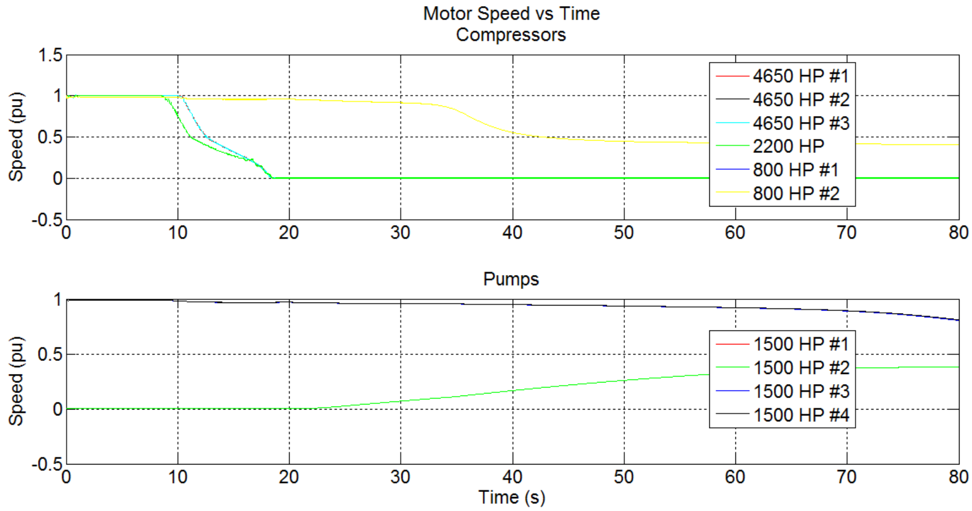

Figure 4. Speeds of customer motors vs. time for the 1500 hp motor start, last to start, without the DVC.

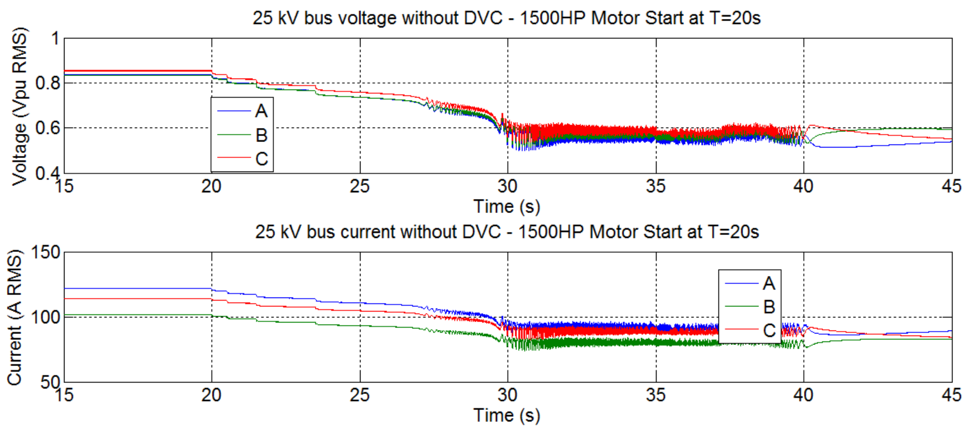

Figure 5. Motor bus voltage (top) and current (bottom) for the 1500 hp motor start, last to start, without the DVC.

B. 1500 hp motor start, last to start, with the DVC

Figures 6 and 7 show simulation results for the 1500 hp motor start in the last-to-start position, but now with the DVC active. The DVC's voltage support enables a successful motor start, as indicated by the motor speeds in Figure 6. Figure 7 shows that the DVC started with one capacitor on, and activates its other switched capacitor when the motor starts.

C. 4650 hp motor start, last to start, with the DVC

Figure 8 shows the motor speeds during a 4650 hp motor start in the last-to-start position with the DVC. The DVC is able to keep the motor bus voltage near 1 p.u., but the 4650 hp motor is not able to reach full speed; instead it settles at about 52% speed and 65% voltage because the 65% voltage being applied to the motor is apparently insufficient to cause the motor to develop enough torque to accelerate to 65% speed, and the RVAT never reaches its second switching threshold, as indicated by the RVAT output voltage/motor terminal voltage shown in Figure 9.

D. 4650 hp motor start, last to start, with the DVC and adjusted RVAT settings

The 4650 hp last-to-start case was resimulated with more aggressive RVAT settings: the second switch threshold was eliminated, and 100% voltage is applied to the motor at 50% speed by bypassing the RVAT's autotransformer. Figure 10 shows the motor speeds for this case. With these changes, the 4650 last-to-start motor starts successfully.

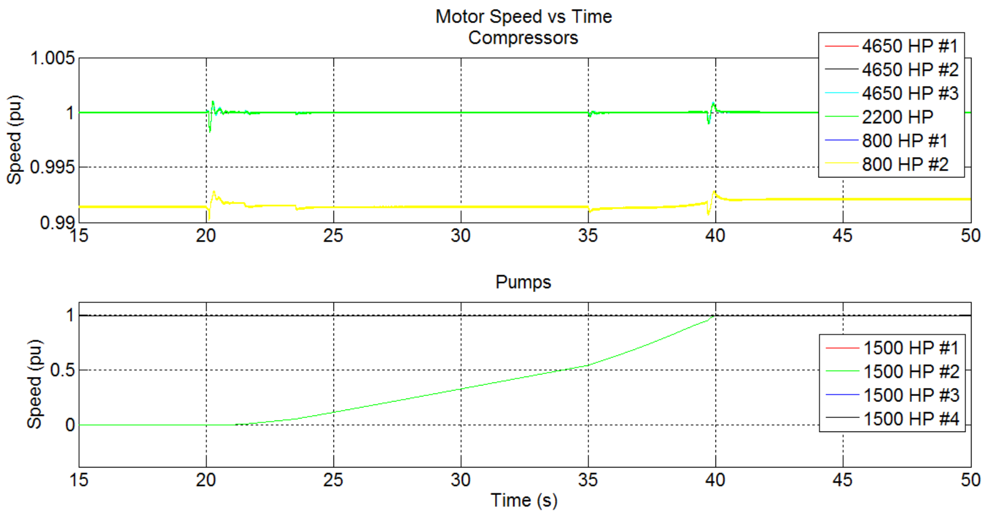

Figure 6. Customer motor speed vs. time for the 1500 hp motor start, last to start, with the DVC.

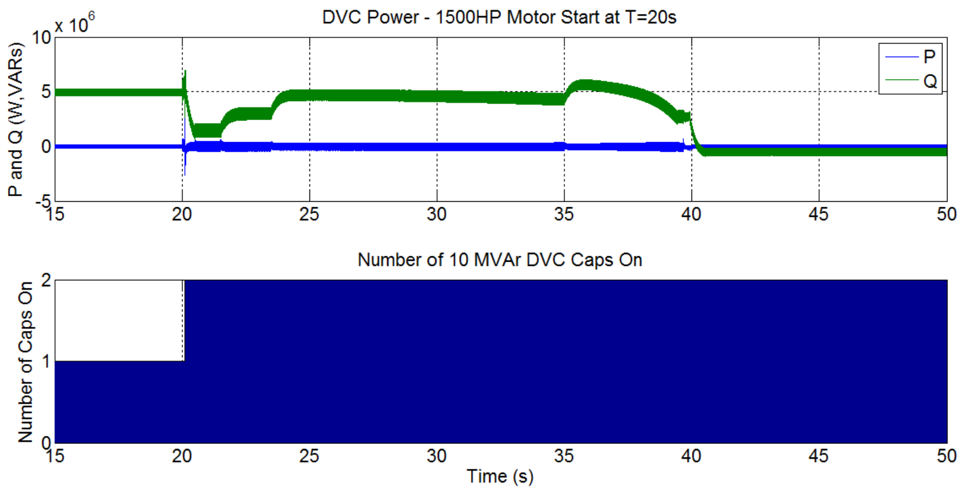

Figure 7. Real and reactive power from the DVC during the 1500 hp motor start, last to start.

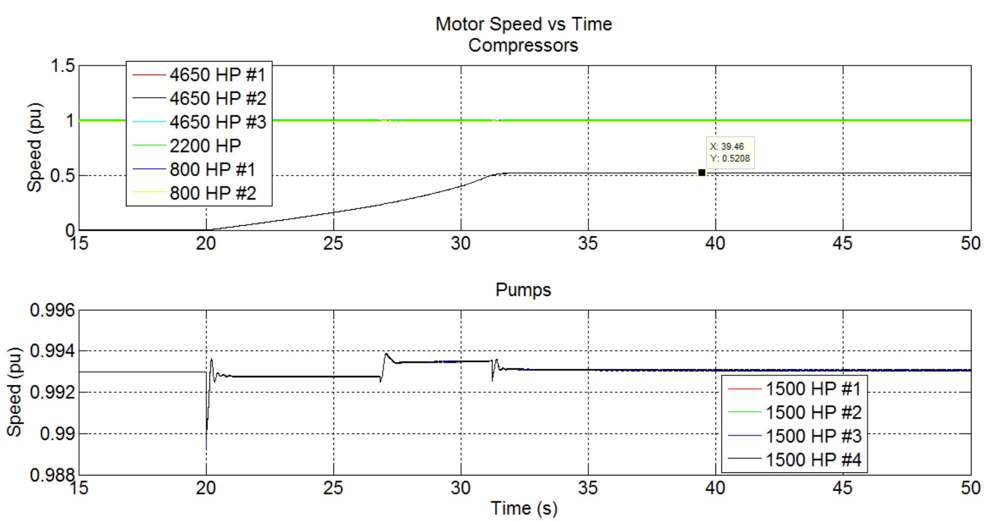

Figure 8. Motor speeds vs. time during the 4650 hp last-to-start event, with the DVC.

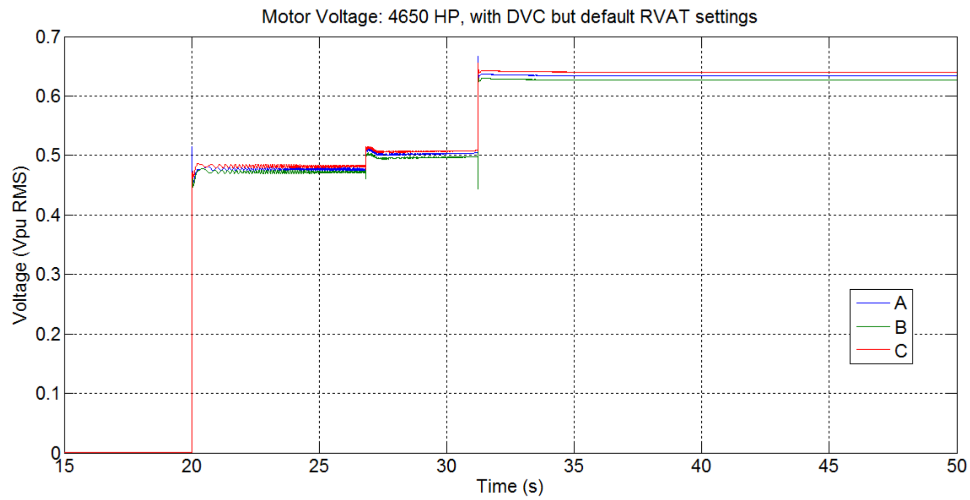

Figure 9. Voltage at the terminals of the 4650 hp motor (output voltage of the RVAT).

Figure 11 shows the motor bus voltage and current during this startup event, and Figure 12 shows the voltage on the terminals of the 4650 hp motor (the output voltage of the RVAT).

Interestingly, Figures 11 and 12 indicate that there is now a short-lived but fairly large voltage spike that occurs at about 35.9 sec, just as the 4650 hp motor reaches synchronous speed. The overvoltage reaches almost 1.16 p.u, and is above 1.15 pu for about 50 msec. Figure 13 indicates that this spike is not caused by any switching in the RVAT. Figure 12 shows the P and Q output of the DVC (top) and the DVC capacitor status (bottom), and Figure 12 rules out a capacitor switching transient as the source of the overvoltage. A zoomed-in view of Figure 13 emphasizing this span of time is shown in Figure 14. Figure 14 shows a sequence of "blips" in the DVC's output, both real and reactive, just as the motor is coming up to speed and right before the 116% overvoltage. This series of blips is caused by mode chatter in the DVC. The DVC uses voltage-triggered parameter scheduling to help tighten its voltage regulation capabilities. At 0.92 per-unit voltage, two things happen: the DVC switches modes and changes its PI regulator gains, and it also momentarily increases the allowed current output to 267% of nominal, to allow the DVC to give the system a "kick" to get it through a transient condition. It gives the system several "kicks" in this instance, and those "kicks" are the blips seen in Figure 14.

Just as the motor reaches full speed, there is a large positive VAr surge from the DVC, and this is where the 116% overvoltage occurs. This final VAr surge is in the wrong direction; downward voltage regulation is needed and the DVC should sink VArs, but instead the VAr surge is sourced, and this causes the transient overvoltage condition. After considerable investigation, it was determined that the surge in VArs is due to a windup issue in one of the integrators in the PI controller. This behavior is related to a specific implementation detail in the modeled controller, and because the DVC manufacturer did not provide this level of detail it is not clear whether the behavior of the model accurately represents the expected behavior of the real system in this specific incidence.

V. Conclusions

The simulations suggest that the existing system cannot support the new customer motor load without mitigation. However, they also show that the DVC is effective as the solution to the problem. Without the DVC, none of the motors could be started in the last-to-start case. The DVC allowed the system to successfully start all of the motors under all circumstances except two: the 2200 hp and 4650 hp motors in the last-to-start case. For both of these, NPPT is recommending that the settings of the RVATs on these motors be reviewed and made more aggressive if necessary ("more aggressive" meaning that higher voltages are applied to the motor sooner, at lower speeds). The simulations were used to suggest new settings for the RVATs.

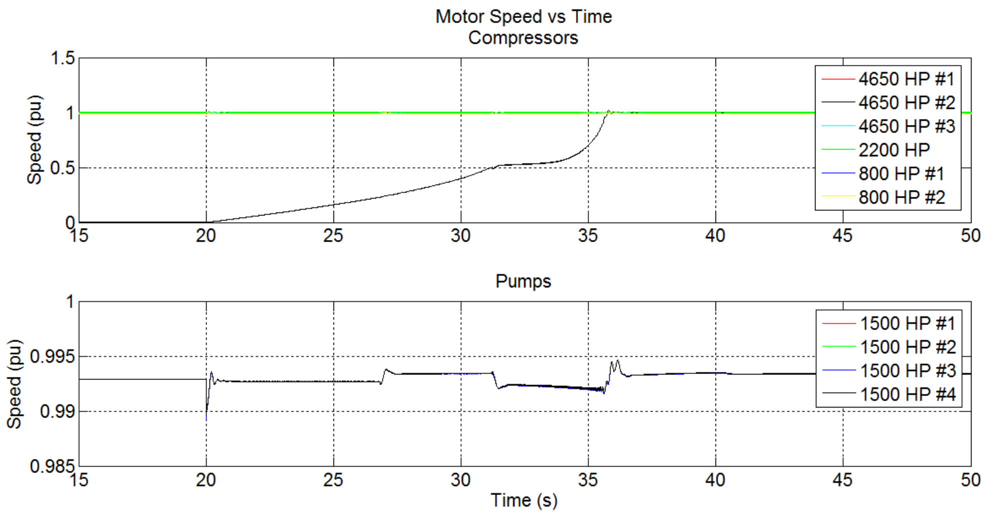

Figure 10. Customer motor speeds in the last-to-start case of the 4650 hp motor, with the DVC and the aggressive RVAT settings.

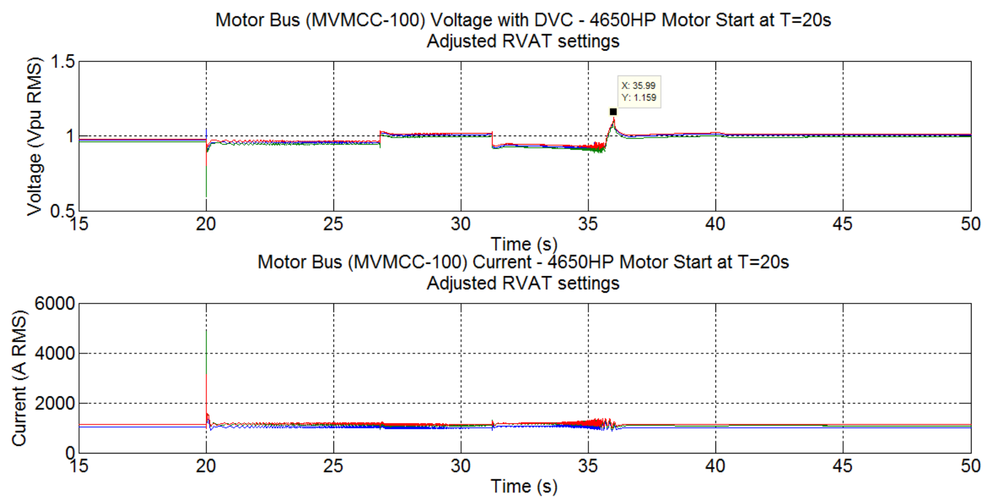

Figure 11. Motor bus voltage (top) and current (bottom) during the 4650 hp last-to-start event, with the DVC and the more aggressive RVAT settings.

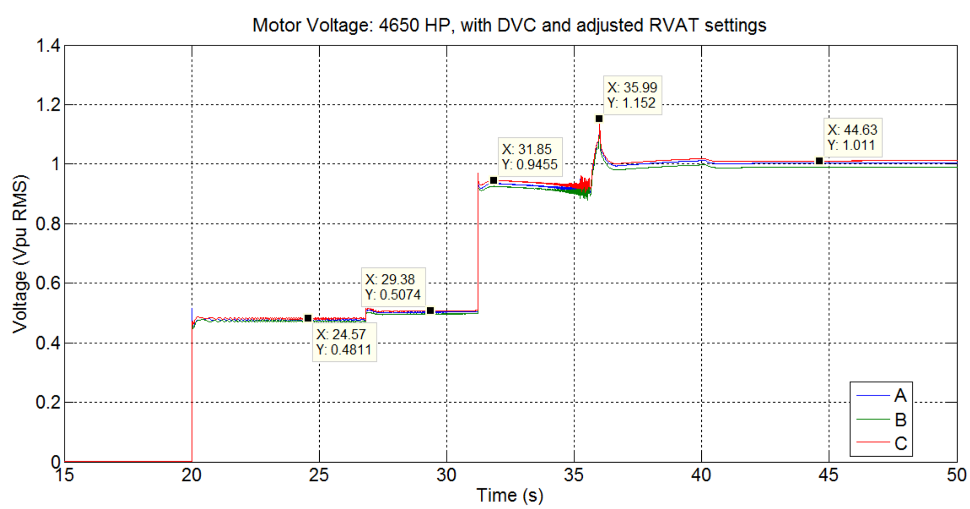

Figure 12. Voltage applied to the terminals of the 4650 hp motor (output voltage of the RVAT).

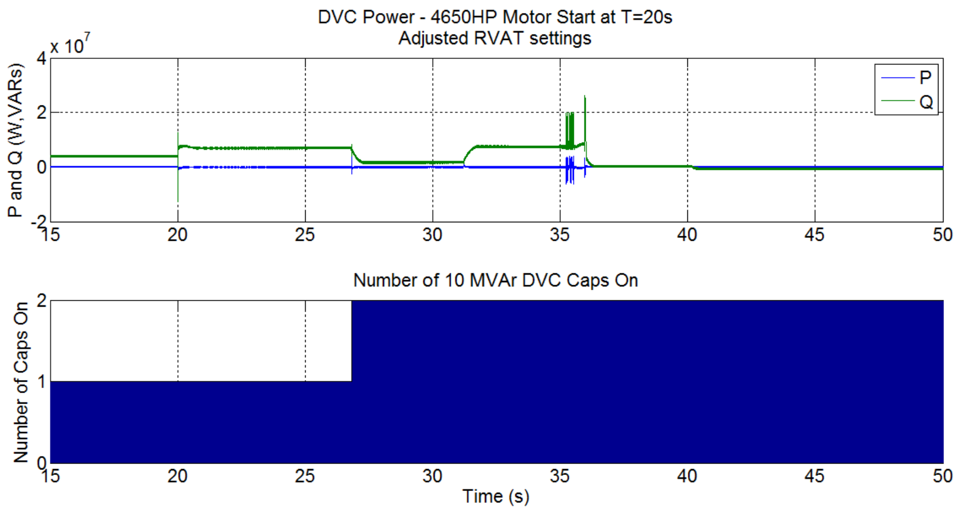

Figure 13. DVC output power (top) and capacitor status (bottom) during the 4650 hp last-to-start event, with the more aggressive RVAT settings.

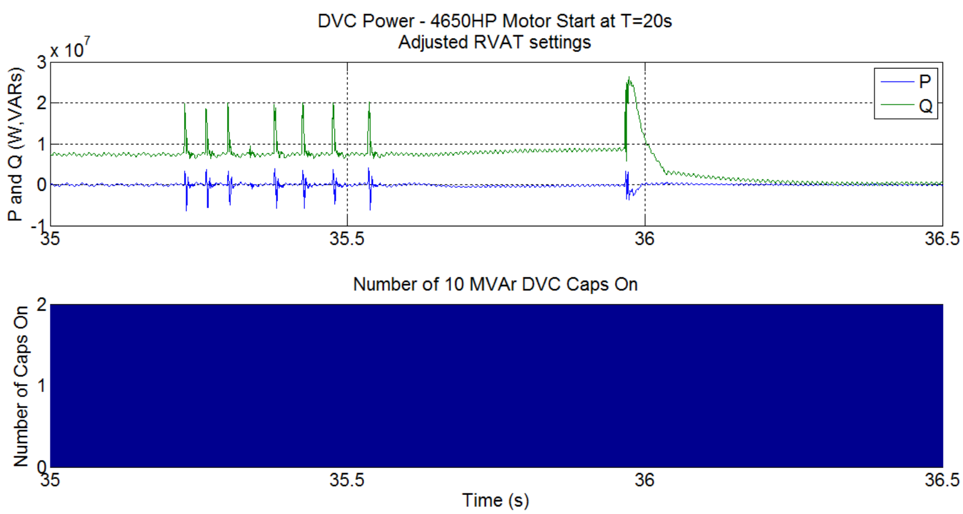

Figure 14. Zoomed in view of Figure 13, emphasizing the time period between 35 and 36.5 sec when the 4650 hp motor approaches and then reaches synchronous speed.

VI. References

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