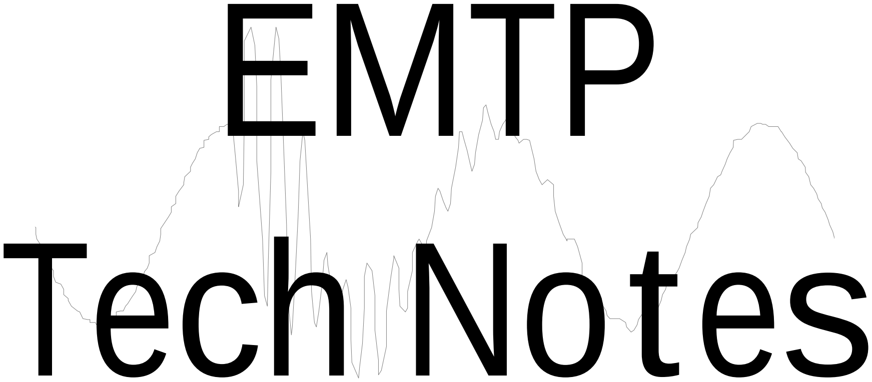
EMTP
Tech Notes



for users of the Electromagnetic Transients Program

Issue # 95-1 ***January, 1995*** ***Editor: Thomas Grebe***

in this issue:

Letter from the Editor:

EMTP Tech Notes is the technical newsletter provided to members of the EMTP User's Group. The newsletter is a quarterly technical publication highlighting contributions from members of the User's Group. This newsletter is published using Microsoft Word for Windows 6.0. If you wish to contribute an article, please contact Susie Brockman or myself for appropriate text and figure formats. Contributions in the following areas are welcome:

Technical articles
Modifications / enhancements to the code
Case studies / unique simulations
Research projects
EMTP data preparation / model development
Modules developed for distribution on the BBS
Letters to the editor / User's Group
Technical paper abstracts
Questions for members of the User's Group

I believe that the exchange of technical information is one of the most important functions of the EMTP User's Group and this newsletter will help to serve the needs of the members. Thanks to the authors for helping to put this issue together. As always, I'm open for suggestions regarding this publication and the User's Group in general.

Thanks for your support

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Transient Analysis

Transient Analysis of Royse 362 KV Circuit Breaker #4630

Introduction

Fault recorder records have shown some restrikes/reignitions on Royse 362 kV circuit breaker (CB). This is a general purpose Westinghouse 362 kV, Type 362SFA40 SF6 gas circuit breaker. This breaker is part of the line protection for the Monticello - Royse 345 kV line. The restrikes have occurred during line dropping and during faults on unfaulted phases. This has raised some concerns about the capability of this breaker and its application on this line.

Transient Recovery Voltage (TRV)

The TRV of a circuit breaker may be defined as the voltage impressed by the attached system across the open contacts of the CB. The most severe TRV occurs when the CB is the last to open for a fault. A CB must withstand this voltage without restrike/reignition of the fault current. If the CB is unable to cope with the TRV impressed upon it by the system, then two events may occur. The first event that may occur is restrike of the fault current. This may cause pitting of the main contacts and will require more frequent CB maintenance. The second event that may occur is a reignition of the fault current. The reignition usually causes major damage to the CB main contact and could cause a catastrophe failure of the CB. Frequent multiple restrikes can lead to reignition.

The most frequent duty for a CB is switching unloaded transmission lines. When an energized transmission line is disconnected by the breaker, a recovery voltage is generated across the opening contacts that can be more than double the maximum rated phase to neutral voltage. This is due to the charging (capacitance) of the line. Even during most faults when the CB switches the line out-of-service, one or two phases of the CB will be required to interrupt a capacitive circuit. Only for a three-phase to ground fault will there be no capacitive current to interrupt.

Circuit Breaker Capability

The ANSI Standards C37.06 addresses both capacitor switching requirements and transient recovery voltage limitations.

Rated Max Voltage	Rated Capacitive Switching Current		Transient Recovery Voltage		
	General Purpose Overhead Line Current	Definite Purpose Overhead Line Current	Rated Time to Crest	Rated Rate of Rise	Rated Delay Time
362 kV	250 amps	315 amps	773µs	1.8 kv/µs	4.9 µs

Information from Fault Recorder

The restrikes are occurring very frequently on one or two phases. They occur within the first half cycle after current interruption. Current amplitude of the restrikes is about 1,200 amps. Normal energized line charging current is about 220 amps (300 amps - 75 amps offset). No multiple restrikes on the same phase are occurring. Line and bus voltages are less than 362 kV phase-to-phase. The following seven pages detail the readings of the fault recorder.

Information from Field Personnel

This breaker has been in service since 1977. The interrupter heads were recently rebuilt to factory specifications due to a failure. The probable cause of the failure was the aluminum ring in the nozzle end of the Teflon orifice on the left contact break becoming dislodged and bridging or reducing the open contact gap. Contact misadjustment and interference with the normal blast of high pressure gas probably caused the aluminum ring to become dislodged.

After the rebuild, tests show that the restrikes are still occurring. The breaker contacts on the other two undamaged phases were clean and free of pitting. All timing and gas consumption tests after the rebuild are within factory specifications. The SF6 gas was tested and no contamination or water was suggested.

Circuit Information

The Monticello - Royse 345 kV line is 96.2 miles long. The line is 795 MCM ACSR bundled (2) conductors constructed in two sections. The first section proceeds 15.35 miles from Royse to Valley Junction. This section is on double circuit steel towers with two circuits and two ground wires in place. The other circuit on these structures is part of the Royse - Valley 345 kV line. The second section goes on 80.85 miles from Valley Junction to Monticello SES. This section is on double circuit steel V towers with one circuit and two ground wires in place. The line's charging is about 85 Mvar at 345 kV.

Figure 1 - Royse / Monticello Area EMTP One-Line

EMTP Line Model

The EPRI/DCG Electromagnetic Transients Program Windows Version 2.1 (EMTP) was used to investigate the Royse CB#4630 restrikes. Figure 1 shows the lines modeled for this study. JMarti frequency dependent line models were constructed using actual structure and line configuration data. The model includes all three phases and includes any mutual coupling. Source impedance data was calculated using the latest short circuit data for the ERCOT system.

Figure 2 - Royse EMTP Bus One-Line

EMTP Bus Model

Figure 2 shows the EMTP bus one line developed for this study. The model is based upon information gathered from station drawings and field inspection. New 345/138 kV autotransformer and 345 kV surge arrester models were developed for this study. The model includes all three phases. Lumped induction parameters were used to model the bus. Source impedance data was calculated using the latest short circuit data for the ERCOT system.

EMTP Results

See following figures for output plots. To provide the worst case transients, the bus voltage phase-to-ground is 296 kV peak (Figure 3). The charging current was calculated at 220 amps (Figure 4). This is very close to the DFR measurement. The calculated voltage across the CB contacts is 650 kV peak with a time to crest of about 8 ms (Figure 5). There were not any reflections or ringing noted on the plots that would suggest any oscillations in voltage or current that would cause a restrike.

Figure 3 - Royse Bus Voltage

Figure 4 - Current through Breaker #4630

Figure 5 - Voltage Across Breaker Contacts

EMTP Restrike Simulation

The restrike simulation is very similar to DFR measurements. The restrike current was calculated at 1,200 amps (Figure 6), the DFR measurement is 1,210 amps. Bus voltages are also similar (Figure 7).

Figure 6 - Restrike Simulation Royse Bus Voltage

Figure 7 - Restrike Simulation Current through Breaker #4630

Conclusion

There does not appear to be any indication of problems with this breaker application on this line. The calculated recovery voltage for line dropping is within ANSI standards for a general purpose breaker. Capacitive current is close to the breaker capability but does not exceed it. It appears that the restrikes are due to the breaker having problems interrupting the capacitive circuit. This breaker has been in service for more than 17 years and it may have been restriking since the line was built. It is experiencing higher than expected restrikes, but they do not appear to be damaging the breaker contacts. There have also not been any observed multiple restrikes on the same phase. It appears that the application of this type of breaker on this length of line is marginal.

Restrikes may also be occurring on other SFA breakers on the TU Electric 345 kV system. Additional monitoring of SFA breakers on the system is needed to determine if restrikes are occurring. Multiple restrikes on the same phase should be closely examined. The magnitude of the restrike current will vary based upon the length of the line. Contacts on restriking breakers should be closely examined during normal maintenance to see if there is any damage.

Possible Solutions

If restrikes are still a concern or are damaging the contacts then one or more of the following solutions should be considered:

- Install shunt reactors on the line side of the breaker. This will drain off the capacitive current and trapped charge. This may also reduce the need for preinsertion resistors.

- Swap this breaker with another breaker on the system. Tests showed that the type SF breaker with two interrupter heads on the Monticello end of this line appears to work without restrike. This breaker could be placed on a shorter line or one that has an autotransformer or shunt reactor attached to the line.

- Replace existing breaker with a definite purpose breaker. It has increased capacitive current interrupting capabilities.

- Replace existing breaker with a 550 kV breaker. The higher voltage classification has better electrical characteristics.

Preinsertion Resistors

A line energization switching study of 100 circuit breaker operations at random times shows that the switching surge flashover rate for this line is greater than 1%. Therefore, preinsertion resistors are necessary and should be maintained on this breaker.

Additional Benefits from Study

Although this study did not identify any specific problems it did provide some added benefits for future EMTP studies. Because of the need in this study, the procedures for developing accurate models for autotransformers and surge arresters have been developed. The increased detail model also helped to provided confirmation of a reduced model for switching surge studies. The comparison to DFR measurements tested and confirmed the validity of our EMTP models. This study also expanded our knowledge of circuit breakers and transients that will provide more confidence in future studies.

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Harmonic Filter Analysis

Design and Analysis of a 12.5 kV Fifth Harmonic Filter

Introduction

With the increase in harmonic generating loads on electric distribution systems, utilities will be faced with the occasional need to install direct harmonic control on distribution circuits to prevent excessive harmonic distortion levels from occurring, especially where parallel resonance conditions are probable. Even if resonance is not a concern, harmonic control still may be necessary on selected circuits where a utility has committed to meeting the voltage distortion recommendations of IEEE Std 519-1992.

Background

In the #93-2 issue of the *HarmFlo+ Tech Notes*, Phill Zimmers and Carl Miller, Western Resources, detailed a case study of a plastic's extrusion facility in Wichita, KS with approximately 2000 kW of 6-pulse DC drives. The Plant, which is primary metered, is served by three customer-owned distribution pad-mount transformers. The case study discusses the problems of handling the **fifth harmonic currents** from these drives by the 12.5 kV distribution circuit and the 10.5 MVA substation serving the plant and the other loads on the feeder. As power factor correction capacitors on the utility distribution line are added in response to seasonal and daily load changes, a severe **fifth harmonic resonanace** develops when a total 3000 kVAr is on line. The resonance causes the feeder current THD to exceed 50% and the voltage THD to exceed 10%. The substation transformer must be derated to 80% of its capacity under these conditions. This, of course, is not tolerable and a solution to the resonance condition had to be found. A temporary Band-Aid was to limit the amount of capacitors permitted on line, awaiting a more permanent solution.

As detailed in the #93-2 issue, the preferred solution was for the customer to install 480 volt harmonic filters in the plant. SuperHarm modeling showed this could be very effective, and economic analysis indicated a fast payback to the customer through reduced power factor penalties on their power bill (less than 2.5 years.) However, after considerable time and effort working with the customer in *mutual* good faith, it came down to the fact that they would not be able to finance the installation of low-side filters. *An alternative would be necessary!*

At this point, the decision was made by Western Resources to install a **fifth harmonic filter** on the 12.5 kV distribution circuit nearby the plant. The placement of the filter would be on the source side of the customer's meter, so they would continue to be subject to the billing power factor penalty. It also was decided to design the filter bank using **typical construction methods** and standards already familiar to our line crews and operators. A pole-mounted, series filter bank consisting of a standard, switched capacitor bank and oil-filled reactors in a grounded-wye configuration was the chosen design. In order to analyze thoroughly both the steady state and transient (switching) activity to which the filter, and its associated fuses and arresters, would be subjected, we decided to model the circuit on EMTP.

Description of the System

The plastics extrusion plant is served by a 12.5 kV electric distribution line and the three customer-owned 12.5 kV/480V 3 phase power transformers. DC motor drives in this facility range from 50 to 500 HP. They are all 6-pulse phase-controlled rectifiers, and consequently are rich in fifth harmonic load currents (Figure 1.) The distribution line, which also feeds many residential and small commercial loads, is approximately three miles in length. Several three phase distribution capacitor banks exist along this circuit to provide voltage support and power factor correction (Circuit drawing, Figure 2.) The source of this circuit is a 69/12.5 kV, 10.5 MVA FA (7.5 MVA OA) substation transformer which is 1.5 miles from the plastics plant.

Design of 12.5 kV Fifth Harmonic Filter

The Electrotek Filter Design Worksheet, modified for a wye connected bank, was used to size elements of the filter bank (Figure 3). Design requirements were that it would be tuned to the 4.7th harmonic, and would need to provide approximately 1000 kVAr of reactive compensation to the circuit (thereby replacing an existing fixed capacitor banks.) The present load from the plastics plant is approximately 2000 kW with 20% average current THD. In order to allow for future expansion of the plant, 3000 kW with 20% average current THD was used as the design harmonic load. A conservative value of 2.5% voltage THD was used as the utility harmonic voltage source (i.e., the ambient voltage distortion level on the distribution system without the plant’s load.)

In a series filter configuration, the *rms voltage drop* across the reactor shows up essentially as a *rms voltage rise* across the capacitor. As an example, for a filter operating at 7.2 kV line to ground, if the design current is sufficient to cause a 300 V drop across the reactor, the voltage across the capacitor will be the sum of the system voltage plus the voltage across the reactor -- 7.2 kV plus 300 V is 7.5 kV. The voltage rating of the capacitor must be adequate to operate under these conditions. The capacitor voltage rating for this design was chosen to be 7.96 kV. This keeps the capacitors operating well below the IEEE Std 18-1980 maximum allowable overload limits as shown on the spreadsheet. It also is a standard voltage rating supplied by capacitor manufacturers. Two-200 kVAr capacitors per phase are used to make up the 1200 kVAr filter bank. (Note: IEEE Std 1036-1992, *Guide for Application of Shunt Power Capacitors*, page 35, suggests not exceeding the 100% rated capacitor values during normal operating duties, reserving the overload capabilities of IEEE Std 18-1992 for contingency conditions.)

The series inductance required per phase to tune the wye-connected bank to the 4.7th harmonic, as calculated by the spreadsheet, is 19 mH. At design operating conditions, with 64 A rms per phase though the filter, the maximum rms voltage across each reactor is 463 V. Oil-filled, 100 A rms, 5 kV, 75 kV BIL rated reactors with 3 kV MOV arresters were specified. The reduced voltage rating (below system voltage) is adequate because the reactors are installed on the low voltage (ground) side of the capacitors, and are solidly grounded at the wye connection point. Under design operating conditions, the filter bank will provide 1028 kVAr of reactive compensation at 60 Hz.

EMTP Used to Verify Design

Once the filter parameters were established, we had several concerns about the performance of the filter, especially under dynamic conditions. We decided to use EMTP to model the circuit and test the design. The output of the model was compared to actual voltage and current recordings from the substation bus. Several cases were run simulating various levels of distribution capacitance on-line. Figure 4 shows the comparison of the actual recordings to the model predictions for 0 kVAr, 1200 kVAr, and 3000 kVAr on-line. The model was accurately predicting the various stages of harmonic resonance as capacitors were staged-in. Figure 5 shows the EMTP simulation of transient activity on the voltage and current in the substation as the filter is energized while 3000 kVAr is on-line. According to the model, the filter should be very effective in eliminating the harmonic resonance condition.

Another concern was the ability of the 3 kV MOV arresters to protect the reactors under two specific transient conditions -- during the filter energizing, and in the event of a fault at or in a capacitor. Both of these conditions were modeled on EMTP. Figure 6 shows the initial energizing activity of the filter-- both the current through the filter and the voltage across the reactor. The 3 kV MOV arrester will clamp the voltage initially, however since steady state is reached in approximately 50 mseconds, the Temporary Overvoltage Capability (TOC) of this distribution class arrester will not be exceeded.

Each phase of the filter is fused with an 80T expulsion link. In the event of a bushing-to-bushing bolted fault across the capacitor that does not go to ground, line voltage would be applied to the reactor and arrester. According to the EMTP model, this causes 780 amps of fault current to flow through the reactor, resulting in 5.6 kV being seen at the 3 kV arrester. It will take approximately 1 second for the fuse to clear. This will exceed the TOC of the arrester, probably causing it to fail. The reactor with its 75 kV BIL rating will not be damaged. Two solutions to this are to use current limiting line fuses, or to install 5 kV arresters in place of the 3 kV. Neither of these are standard equipment for this company. Recognizing the fact that this situation does exist, from a practical view point, it is unlikely that a fault at the capacitor could exist across the bushings without going to ground. If the fault does go to ground, the reactor and arrester are essentially bypassed. With this consideration in mind, it was decided to stay with the original design.

Results of the Filter Installation

The filter was installed on the main circuit, approximately 20 feet from the three-phase branch to the plastics plant, toward the source. It was energized on November 7, 1994 (Figure 7 - photo). A BMI 3030 power analyzer and a BMI 8800 disturbance analyzer were installed at the substation bus to record the before and after steady state data, as well as the transient activity resulting from energizing the filter. A Fluke 41 harmonic meter was used to measure the series current through the filter. The before snapshot (prior to energizing the filter showed an average voltage distortion level of 4.4% and an average current distortion level of 21.1%. The current spectrum showed 19% or 32 amps of 5th harmonic current (phase ‘a”.) There were two distribution capacitor banks on line at that time -- a total of 2100 kVAr (a 900 and a 1200). Figure 8 shows this **initial data**. Overlaid on the before waveshapes are the EMTP projections for similar conditions -- a very good match!

The BMI 8800 disturbance analyzer recorded the filter energizing event as a waveshape fault. Single phase oil switches are used at the filter which causes each phase to close at slightly different times -- several cycles apart. Figure 9 shows the waveshape fault recorded at the substation as phase ‘c’ closed (phases ‘a’ and ‘b’ had closed a cycle or two previous to this.) **The fifth harmonic** is obvious in the current just prior to the close event. A slight capacitor switching transient can be seen on the voltage waveshape as the filter is energized. Within 1.5 cycles, the **fifth harmonic** component in the current is no longer evident. ***The filter has eliminated the resonance condition!***

A subsequent snapshot of the voltage and current waveshapes approximately two minutes after the filter was energized verifies that the resonance has indeed been eliminated. Current distortion has been reduced from 21.1% down to 6.8% (now dominated by the third harmonic), and the voltage distortion was reduced from 4.4% to 1.1% (Figure 10). Overlaid on this graph is the EMTP model waveshape predictions for similar conditions. Note again the excellent match. The reactive power measurements from the BMI 3030 indicated that 1029 kVAr has been added to the circuit. The Electrotek Filter Design Worksheet had predicted 1028 kVAr of additional compensation, and the EMTP model had predicted 1029 kVAr. There was approximately 3100 kVAr of compensation on line at that time. Recall from the *Background* section of this report that this was the **worst** condition for resonance prior to the installation of the filter.

Without the filter in place and with that amount of compensation on line, we would have expected current distortion levels in excess of 50% and voltage distortion in excess of 10%, along with a significant loss in transformer capacity due to derating. The filter completely eliminated these problems!

Finally, measurements and snapshots were taken at the filter itself with the Fluke 41 single phase harmonic meter. Measurements of the currents were made in each phase leg to ensure balance. They each were conducting 52 Arms -- the current spectrum showed 50 A of fundamental and 13 A of fifth harmonic current. Of course, the fifth harmonic content is a function of the amount of harmonic loads (DC drives) the customer was using at that time. The filter has been designed to handle significantly more harmonic current to allow for contingencies and future expansion of the customer's load. The design called for a minimum of 43 A of harmonic current capacity in the filter. At the current conditions, the filter is operating well within its capability limits. Figure 11 shows that snapshot of the current through the filter. Overlaid on this again is the EMTP model prediction for similar harmonic load conditions -- another excellent match.

Conclusion

EMTP, SuperHarm, and the Electrotek Filter Design Worksheet all proved to be the perfect analytical tools to design and simulate the operation and effects of a distribution line harmonic filter. **EMTP** was especially useful in analyzing the transient activity due to switching and faults.

We are pleased with the performance of the filter and expect to get many years of good service from it. This 1200 kVAr, 12.5 kV filter bank cost approximately thirty thousand dollars installed. The cost of low-side filtering by the customer was estimated at approximately **five times** that much. In cases as this one, where the service distribution transformers are customer-owned or of sufficient capacity to not be a concern, this certainly is a cost effective solution to distribution harmonic resonance problems.

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Modeling

Use of Universal Machine Model and TACS in EMTP

The Electrical Engineering Department at Clemson University, Clemson, SC, requires graduate students with a focus in Power Engineering to take a graduate course entitled. “Power System Transients”. At the backbone of this course, is the use of EMTP as the fundamental simulation tool for transient phenomena on power systems. Not only does the course cover modeling of basic circuit elements, but also the modeling of machines and control schemes using EMTP’s built in Universal Machine (UM) module and TACS.

A simple example that combines the use of the Universal Machine Module and TACS is the modeling of an induction machine and a drive system that is used to control the speed of the machine [1]. This simple example can then be the basis for an extensive analysis into the behavior of machines and drive systems under certain transient conditions such as during voltage sags.

The following are two examples which are presented to students as a starting point for more advanced simulation exercises.

Induction motor simulation using Universal Machine Module

A three phase squirrel cage induction motor is simulated as a type 3 (UM) machine in EMTP. A simple network as shown in Figure 1 can be used to illustrate startup characteristics of an induction motor under no load conditions. The mechanical network models the moment of inertia (M1), friction and widage losses (damping, D1. and load torque. The moment of inertia is modeled by a capacitor, whereas the load torque is modeled by a current source of very low frequency, so that during the simulation it is practically constant. The resistor used to mold the friction losses can be calculated using a knowledge of the power loss (due to friction at rated speed, and by assuming that the loss varies linearly versus speed. For example, if the losses are 2 KW at a rated speed of 3% slip for a 4-pole machine, then the friction coefficient, B is given by :

where $B=2KW/\omega_{rated}^{2}$N-M-s/rad

$\omega_{rated}=o.97*1800*2*\pi/60$ rad/2

which gives us, $B=0.06$ N-M-s/rad

therefore, R=1/B = 16.67 Ω

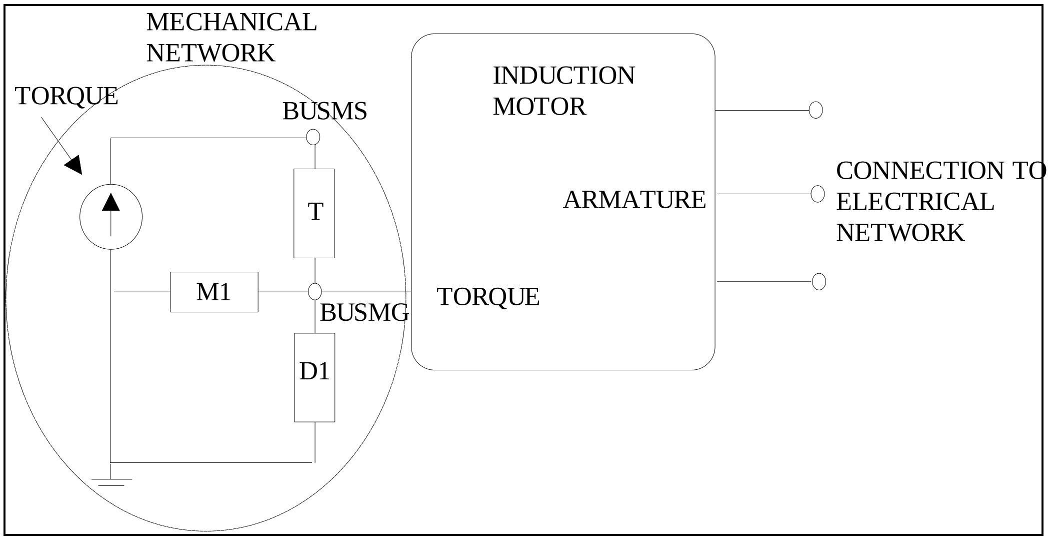

Figure 1 - Induction Motor Model

No load startup of the machine is accomplished by using the “decoupled” mode of initialization as opposed to “automatic” initialization. Decoupled initialization requires the specification of initial machine currents and speed which is all taken to be zero. Figures 2 and 3 illustrate the torque and speed transients. As expected the torque settles to no load values while the speed settles close to its synchronous value.

Figure 2 - Motor Startup (no load) torque characteristics

Figure 3 - Motor Startup (noload speed characteristics)

Line Frequency Variable Voltage Drive Simulation Using TACS

The use of TACS as an algebraic and logical processing unit is illustrated through a simple drive model. The main purpose of this example is to show the student how TACS is used to generate gate pulses for thyristors which are the main elements in the drive circuit.

The line frequency variable voltage drive circuit model is shown in Figure 4. It is essentially comprised of a pair of thyristors back-to-back on each phase. The gate pulses for these thyristors are generated using the logic illustrated in Figure 5. This control scheme is simulated in TACS by using the integrator block (device code 58) which integrates a step function to produce a ramp. The integrator is also controlled by the bus voltage which forces the ramp to zero every time the voltage goes negative. In this manner, a saw tooth function is generated. This function is compared to a set value to produce a set of pulses whose width is then modified by certain logical operations. This leads to the final gate pulse (see Figure 6) which is the input to a type 11 switch (thyristor).

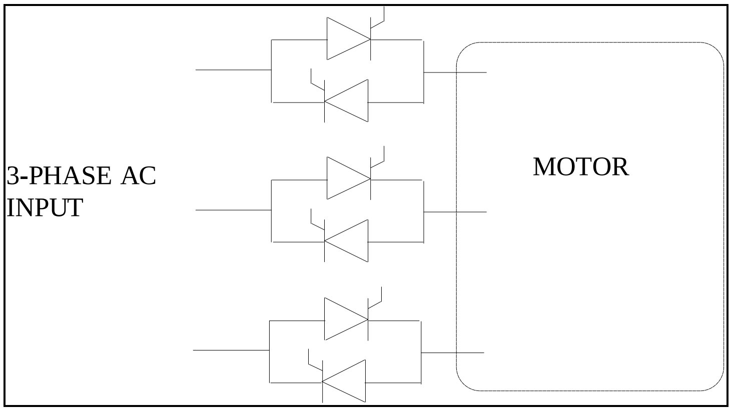

Figure 4 - Line Frequency Variable Voltage Drive

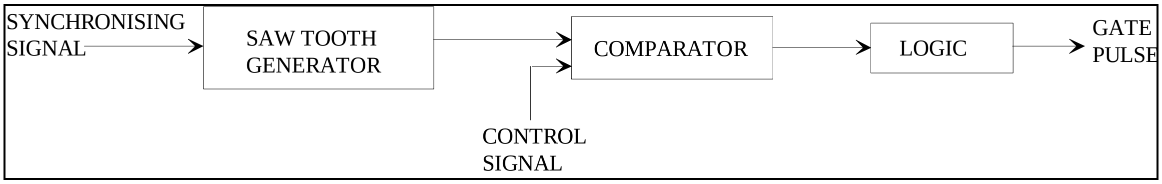

Figure 5 - Control Scheme Used to Generate Gate Pulses

Figure 6 - Gate Pulse

Final 7 and 8 shows the current and voltage at the motor terminals. As expected, one sees the notching effect in the voltage and the high levels of current harmonics generated by the drive.

Figure 7 - Current at Motor Terminals

Figure 8 - Voltage at Motor Terminals

The ability to model machines and drives is invaluable in looking at how they interact with a power system. Using the UM module and TACS in EMTP, greatly enhances the students experience in understanding the theory behind the operation of such devices and their interaction with power system transient phenomena. Given such a simulation tool, students can now spend most of their time in the analysis of classroom problems that closely parallels real work problems.

References

[1] Ned Mohan, "Computer Exercises for Power Electronics Education." Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455.

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