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REDUCED FREQUENCY MOTOR STARTING FOR THIRD WORLD POWER SYSTEMS

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ABSTRACT OF THESIS

REDUCED FREQUENCY MOTOR STARTING FOR THIRD WORLD POWER SYSTEMS

People in modern industrialized societies live a blessed life relative to those who do not when it comes to some modern conveniences. While many think nothing of flipping on a light switch or running electric appliances, there are people in third world countries could not imagine such things. As service projects are being undertaken to bring such conveniences to those less fortunate, there often is the harsh reality of a strict budget. An item that commands a large portion of said budget is often the diesel generator used to provide the facility with electricity. Generators serving motor loads are typically oversized due to a large kVA starting requirement. This paper addresses an approach to this problem by temporarily restricting the generator fuel supply by pulling back the rack of the mechanical governor reducing the frequency and voltage output as a motor load is switched onto the system. By reducing the voltage and frequency output of the generator, the motor is switched on at a time when its typically poor power factor and resulting kVA requirement is mitigated by the lower voltage and frequency allowing for a smaller generator to be used.

KEYWORDS: Reduced Frequency, Motor Starting, Third World Power, Reduced Voltage, Mechanical Governor

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June 30, 2009

REDUCED FREQUENCY MOTOR STARTING FOR THIRD WORLD POWER SYSTEMS

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June 30, 2009
Date

RULES FOR USE OF THESES

Name Date

THESIS

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The Graduate School

University of Kentucky

2009

REDUCED FREQUENCY MOTOR STARTING FOR THIRD WORLD POWER SYSTEMS

THESIS

A thesis submitted in partial fulfillment of the
Requirements for the degree of Master of Science in Electrical Engineering
in the College of Engineering at the University of Kentucky

By

Taylor Andrew Begley

Lexington, Kentucky

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Lexington, Kentucky

2009

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Chapter 1: Introduction

Our standards in life are often a product of our economic status. A man accustomed to eating filet minion may scoff at the idea of eating a chopped sirloin. Similarly, a man who has very little to eat would be more than happy with that same sirloin. This situation is analogous to the problem that is presented in this paper. The solution to the surveyed problem is one that could greatly improve the lives of people in impoverished third world countries, but would be more than likely unacceptable to those accustomed to the living standards in places like the USA.

The needs and problems encountered by those in third world countries seem to be limitless. In this paper, I will describe a solution to a problem that would make life a little better for those that are less fortunate. This issue is the availability of an affordable means of obtaining water that is suitable for consumption. Unfortunately, the surface water, including creeks, streams and lakes, in many third world countries are extremely polluted from various sources. Not the least of these sources is sewage. As you can image, the lack of sanitary drinking water plays a large role in the spread of disease in these societies. There are other sources of water available that are far less dangerous. Unfortunately, those sources may be 80 or 100 meters deep into the ground. Once it is reached, there still is the issue of bringing the water to the surface, and preferably into a water tower for distribution to the community.

A relevant issue to explore is the current infrastructure in these regions. As one would expect, these poor countries often lack the funds to have the luxury of a reliable power grid like we enjoy here in the U.S. The power that exists in many of these places could be described as erratic at best. To many of us, this would prove to be immensely frustrating to not be able to count on having a reliable power source. Natives of these areas, however, are often simply thankful for any power that they have and are less concerned with the fact that outages lasting hours, or even days or weeks at a time are not uncommon.

Again, consider the challenge of providing the community with adequate, relatively clean water from deep within the earth. Normally, while the power to the community is flowing, the source can be treated as an infinite bus. There is no issue with running all of the common electrical loads that exist in the community. In addition, starting and operating an induction motor that will be powering a pump that will bring the water from the depths to the community's water tower is a trivial issue. However, a problem arises when the power provided by an unreliable utility fails.

Because the local utilities cannot be counted on for reliable power, there exist many service projects that involve providing these communities with backup diesel generators to run their most vital loads. One of these loads would likely include power to run a pump in order to provide the community with sanitary drinking water. This is the part of the story where this paper enters the scene. As mentioned before, the depth required to reach sanitary water is likely in vicinity of 80-100 meters and the pump will have to be relatively large to provide the necessary head to push the water to the height of a water tower located above the surface. It would not be uncommon for this vertical distance to exceed 100m.

When these communities are working to upgrade their facilities with backup power generation via a diesel generator, financial resources are at a premium. As you can imagine, these communities have budgets that are very tight, so everything done in the process must be done with the utmost cost efficiency in mind. Even a few hundred dollars could be enough money to make or break many projects. In order to look at where money can be saved in these situations, we must look at the “big ticket” items. Obviously, the big ticket item in this situation is the generator itself and the cost for the generator is directly proportional to its size. A higher power requirement results in a higher cost. The purpose of this paper is to explore a way in which to reduce the required generator size, thus reducing project cost, without the use of additional equipment that would further raise the project cost or complicate the operation of the system.

Chapter 2: Presentation of the Problem

To further refine the definition of this problem, more specificity is required. In aggregate, the common electrical loads that are involved with lighting, receptacles, etc. act in a somewhat linear fashion and will never require more power to run them than what is required when run in rated steady state conditions. Simply put, there is nothing difficult or interesting about the way a light bulb responds in different scenarios as far as its power requirements. Motors, in particular larger motors such as the one used to pump the water from the well to the tower, act in a very interesting way when exposed to different electrical situations. They certainly have different requirements as various voltages and frequencies are impressed upon them. The requirements of a motor when running at rated conditions and the requirements for the same motor when that motor is being brought up to rated speed vary greatly. The inrush current that is required when starting an induction motor with full voltage applied typically is on the order of 4-5 times the rated operating current. More importantly, the kVA requirement of starting a motor is also much greater than the steady state requirement. The spike in current, in conjunction with the poor power factor at low motor speeds, results in this huge kVA spike.

The kVA capacity of the generator powering the system is the limiting factor. The ability to supply adequate real power (kW) is certainly a constraint, but the kVA demanded by this system is even a more prominent issue as the motor is accelerated to rated speed. At the low speeds that occur during startup, the motor will draw high currents at a very poor power factor. When huge currents are drawn during a full line voltage start of a motor, they are drawn at such a poor power factor that measuring the kW required by the system does not reveal the entire picture. Because of the poor power factor, the requirement of the motor is better represented and described by looking at the kVA required. Any technique that could reduce the kVA spike or offset its effects would allow the system generator to be sized smaller. By slowing down the generator, causing a drop in voltage and frequency, the difficulties and limitations presented by poor power factor are somewhat mitigated. Also, by sizing the generator smaller, you reduce the use of fuel and allow the generator to run at a higher percentage of its capacity, allowing it to be more efficient.

Consider a system that consists of a common load (lighting, receptacles, etc.) that is 20 kW with a 0.85 power factor and an induction motor that is driving a 20 hp water pump. In steady state, after the motor is up to speed, the system power requirement is roughly 43 kVA. The problem is that during the startup of the motor, it spikes the required kVA, bringing the apparent power requirement up to roughly 105 kVA. Because of the few seconds it takes to start the motor, the project must buy a generator that is capable of providing 244% of the actual steady state load after the motor is started. If generators cost $400/kVA, then you are spending an extra $24,800 on a generator that will only be run at full capacity for less than a few seconds per motor start. For projects with a very limited budget, that $24,800 may be not available and may be enough to kill the project.

The purpose of this paper is to show a solution to the above problem that is appropriate for the environment in which it is used. The objective is to provide a more cost effective use of the limited project budget. Secondly, the solution must be rugged and simple to operate. Lots of delicate electronic controls and/or a complex manner in which the solution is implemented would contradict its applicability. Brief disturbances to the supplied power are not an issue in this situation since poor power quality is commonplace.

A literature search has only identified one application that directly relates to the principle utilized in this study [1]. In reference 1, an oil-field pump is supplied by a dedicated generator where the advantage of reduced voltage and frequency are implemented to reduce the size of the required generator. However, this reference does not provide any information on the theoretical performance analysis, if such was done. Otherwise, it appears that this problem is one that has not been studied, and understandably so, since the resulting power quality normally would not be acceptable in an application having loads connected in parallel with the pump.

There are currently other ways that the problem in this study is being addressed. The method of using capacitor banks or series reactors or the use of solid state motor starting would all be nice, but would result in extra equipment and extra costs.

On the other hand, the underlying principle of reduced voltage and frequency start of an induction motor is a common occurrence when the well-known constant Volts/Hertz inverter drives an induction motor. In a general sense, the concept introduced in this thesis mimics the Volts/Hertz inverter without the associated cost of the power electronic equipment.

Chapter 3: Presentation of the Solution

The beauty of the solution to the problem of interest in this paper is in its simplicity. In order to save money and use a smaller generator, achieving the goals laid out in the previous section, inherent features of the generator can be used. The primary factor causing the generator to be sized larger than the required steady state load, is the spike in current due to the starting of the motor. When starting a motor at full voltage and frequency from the power source, it is common to experience significant spikes in current and kVA demanded. In order to avert this problem, one can reduce the frequency and the voltage output of the diesel generator.

The Figure 1 shows the kVA requirements as a 22 hp motor and pump are accelerated to rated speed. It is evident that the starting kVA requirement of a system running at 59V and 20Hz (1.33kVA), which are the minimums set for the model simulations, requires significantly less apparent power than the full line starting parameters of 277V and 50Hz (27.20kVA). Below the aforementioned minimum starting speed, the generator has difficulty providing the necessary power to supply the pump with enough torque to begin its acceleration. The power produced at this lower frequency, however, is adequate to begin the acceleration of the motor-pump. While the time for the pump to accelerate to full speed is increased, this is a reasonable tradeoff for the reduction in demanded power from the generator. This capability of reducing the kVA requirement at the low speeds that exist during motor startup is the crux upon which the entire solution is built.

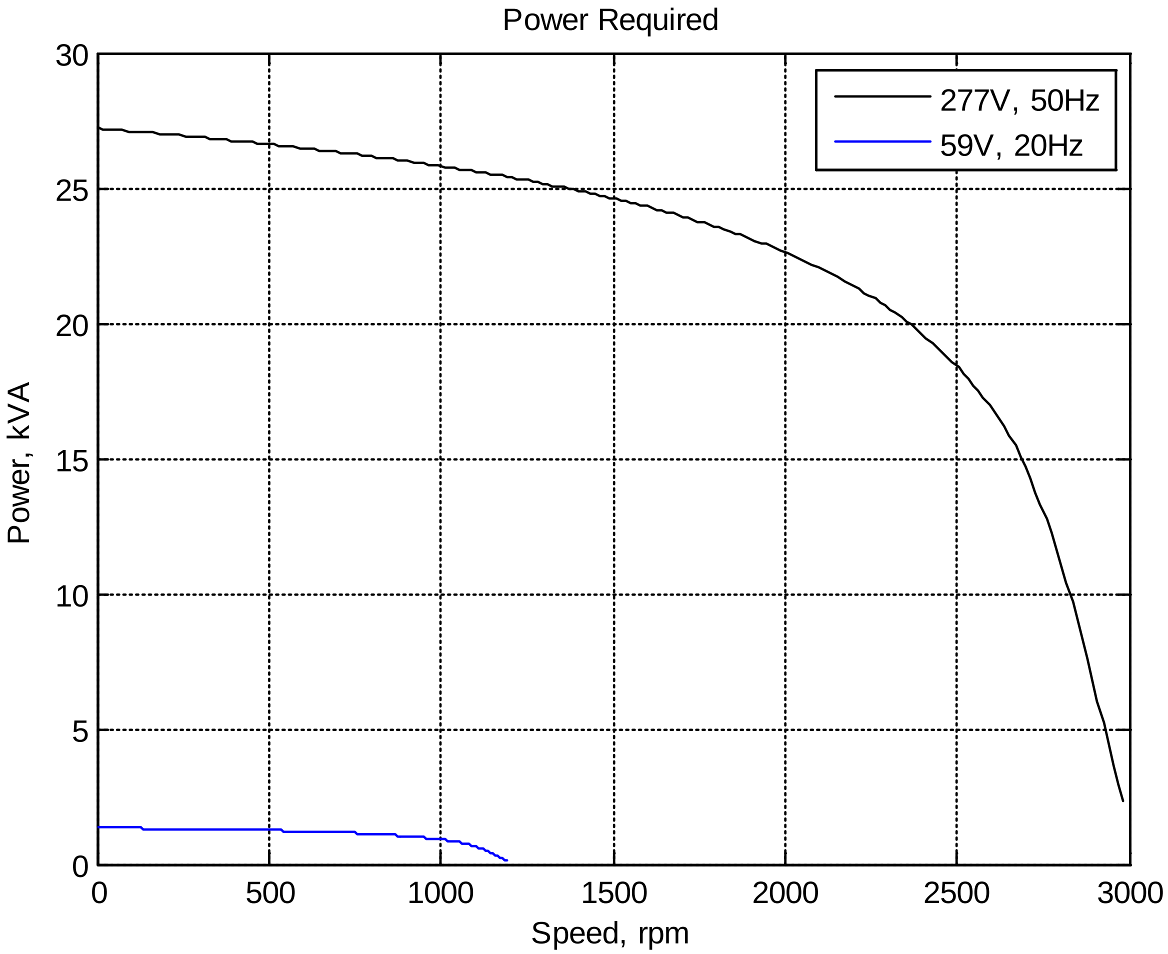


Figure 1: Required Apparent Power for Startup with Different Parameters

This reduction in voltage and frequency can be achieved somewhat simply if the generator is equipped with a mechanical, fly ball type governor. Figure 2 [4] shows the mechanics of a fly ball governor system.

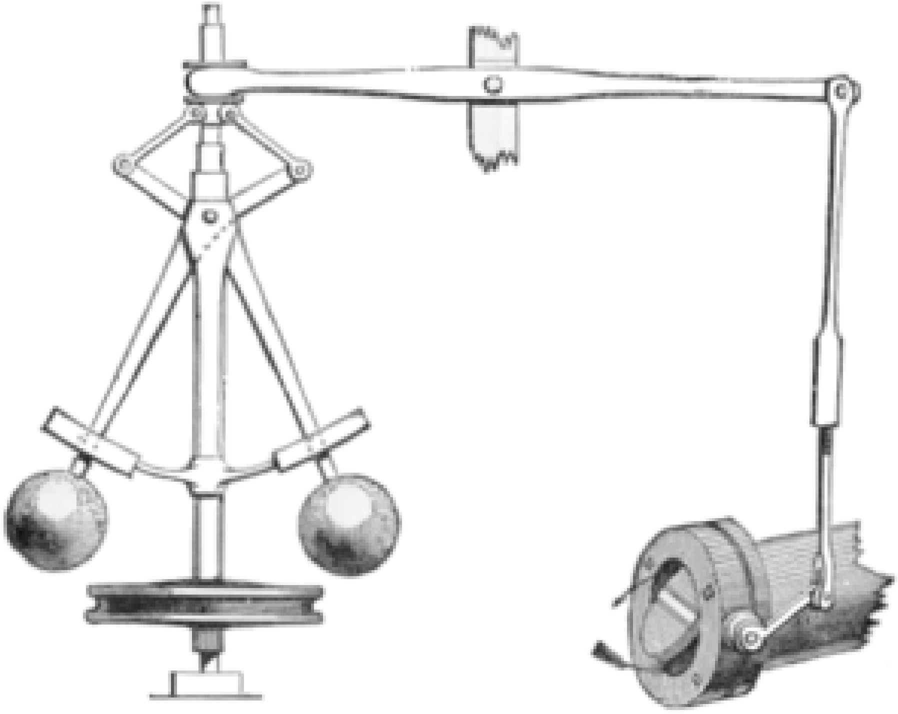


Figure 2: Flyball Governor

The reduced diesel engine speed is achieved by pulling back the rack controlling fuel into the generator, thus reducing its speed. When the rack is released, the generator will respond by giving the generator more fuel and accelerating the engine back to full speed. Further, an adjustment of a dashpot or spring attached to the rack can be an easy, and indeed rugged, solution to adjusting the time desired to bring the engine back up to full speed. Put simply, one person first pulls back the rack. Next, that person (or another person) switches the induction motor on line and then the rack is released. This allows the generator to accelerate back to full speed, eventually providing the full rated voltage and frequency to the system. All of this occurs without any adverse affects on the generator.

As seen in Figure 1, the lower voltage and frequency applied to the induction motor allows the kVA requirement to be considerably lower than a full line start, while still providing ample torque to bring the motor up to speed within a very reasonable time frame. In fact, by the time the generator reaches full speed, the electrical transients involved in getting the motor up to speed are complete. Because of this, the large spike in electrical requirements can be partially, if not completely, offset before the full rated voltage is regained and applied to the induction motor.

The System Model

In order to model this entire system, it was broken into several key components, each of which can easily be modified to fit in the parameters of a given situation. A simplified schematic of the model is shown in Figure 3 and a description of each component follows. The model is tested and observed in the time frame required to bring the entire system to steady state. For each increment of time tested, the model is evaluated completely, the results are stored, and then the model moves to the next iteration until the desired test time is elapsed. The model was designed and tested using

MATLAB. The code written to run the model and develop most of the plots in this document can be found in the Appendix. The overall system that is about to be described will serve a specific purpose. That purpose is to provide electrical service to a system that includes common loads (receptacles, ceiling fans, etc.) as well as bringing online an induction motor that is powering a pump that will provide a minimum of 120m of head to bring water from a deep well to a storage tower. The model that was developed to simulate this system is remarkably versatile and can be, and will be, tailored to evaluate the advantages of this system in a variety of different circumstances.

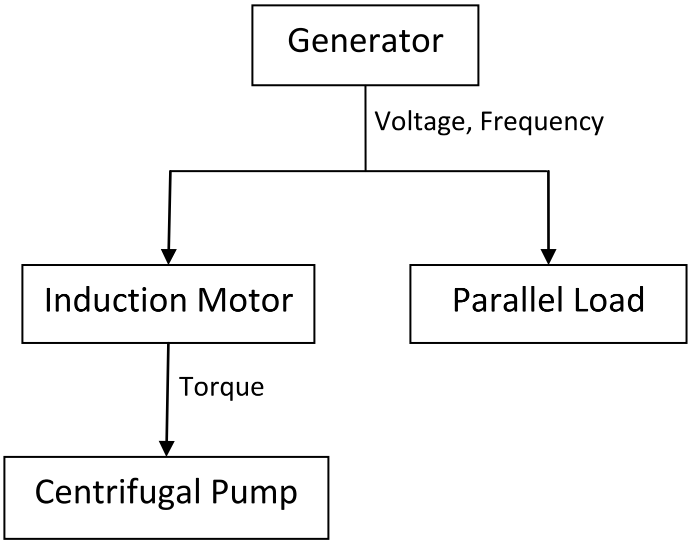


Figure 3: System Schematic

The Generator

The action on the generator is the main mechanism in the system that is going to allow this method to be successful. As discussed before, the rack of the generator will be pulled back, reducing the generator speed to a selected percentage of synchronous speed. In the model, a 4 pole 50 Hz generator is used, which has synchronous speed of 1500 rpm. After the rack is released, the generator will accelerate back to the synchronous speed in a given amount of time. This amount of time can easily be adjusted in the model. In practice, it could be adjusted by altering the dashpot that damps the rack movement back to its initial, full speed position. It is the assumption of this simulation that it will accelerate to synchronous speed exponentially. For example: if it is desired that the generator to be reduced to 40% speed and recover to full speed in ten seconds, the generator output frequency would look like the speed-time curve of Figure 4.

The generator speed-time curve is modeled using the following formula to replicate the exponential rise back to synchronous speed.

$$n_{generator} = n_{sync\,hronous} - \left(n_{sync\,hronous} - n_{initial}\right) * e^{-t/1.7} \tag{1}$$

Where

$n_{generator}$ is the output speed of the generator.

$n_{sync\,hronous}$ is the synchronous speed of the generator (1500 rpm in this case).

$n_{initial}$ is the starting speed to which the generator is reduced with the rack is pulled back.

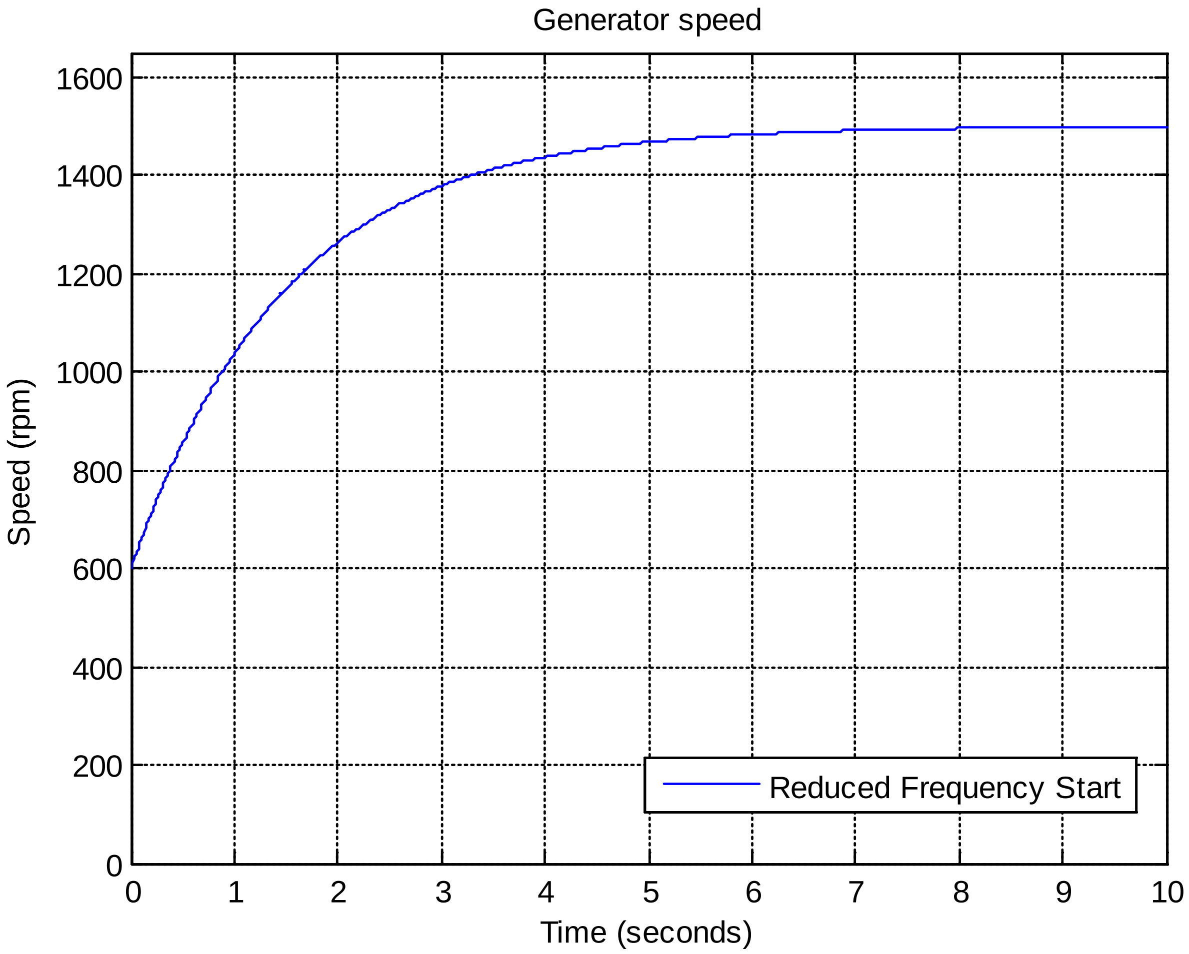


Figure 4: Sample Generator Waveform

1.7 is an arbitrary time constant that determines the length of time for the system to return to full speed.

Every generator will have its own voltage-frequency characteristic. However, the vast majority will fall in one of two categories depending on the type of excitation involved. If the generator is separately excited by a shaft mounted auxiliary generator, it will have a characteristic curve that is quadratic in shape until reaching a pull-up voltage that brings the output up to the fully rated voltage. This occurs due to the ability of the generator's exciter to temporarily provide the extra voltage to push the output voltage up the rated voltage. It is not uncommon for the exciter to be able to compensate for a 15%-20% dip in voltage. In the simulations for this paper, the voltage is pulled up to its full line level at 85% of full frequency. Another key element to this analysis is the internal impedance within the generator. The generator approximate equivalent circuit is shown in Figure 5. Due to the generator internal impedance shown in the figure, the terminal V_t, is not directly proportional to the excitation voltage E_f. On the contrary, V_t, which is the voltage seen by the induction motor and the parallel load, will be characterized by the following equations:

$$V_t = E_f - V_g \tag{2}$$

$$V_t = E_f - j\omega L_S(I_a) \tag{3}$$

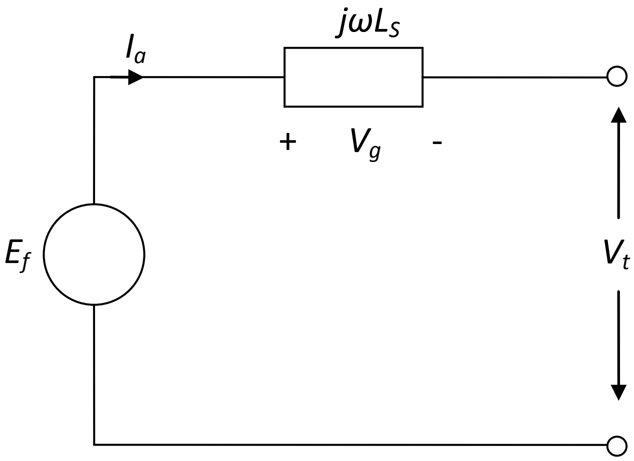


Figure 5: Approximate Generator Equivalent Circuit

At 85% of full frequency when V_t reaches full voltage, which is the case of this study is $0.85 * 50\ Hz = 42.5\ Hz$ and $460/\sqrt{3}\ V \cong 265.58\ V$, the voltage is regulated to hold full voltage. When operating below that threshold frequency, the voltage-frequency curve modeling E_f is given by the following equation.

$$E_f = \frac{E_{fMAX}}{{f_{min}}^2} * f^2 \tag{4}$$

Where

E_f is the excitation voltage of the generator

E_{fMAX} is the maximum available excitation voltage of the generator

f_{min} is the minimum frequency at which the exciter can maintain the regulated generator voltage (85% of rated frequency in this study)

f is the frequency output of the generator

This curve is shown in Figure 6.

If the generator is excited by its own rectified output, a frequency sensitive excitation control can be designed to render a voltage-frequency curve that is linear below a selected frequency. Regulated voltage is maintained above that frequency. The curve in this region is modeled by the following formula and is shown in Figure 7.

$$E_f = \frac{E_{fMAX}}{f_{min}} * f \tag{5}$$

Because the shaft speed of the motor is not constant, it is very difficult to analytically predict the impedance of the motor at a given time. This further makes it difficult to find the system current and the voltage drop across $j\omega L_S$ which would allow E_f to be calculated. In order to find E_{fMAX}, a trial and error method was used until the resulting terminal voltage $V_t$was found to be piecewise continuous. The model in this study will primarily be using the self excited generator, but the differences in the performance of the system using the two different methods of excitation will be evaluated in Chapter 4.

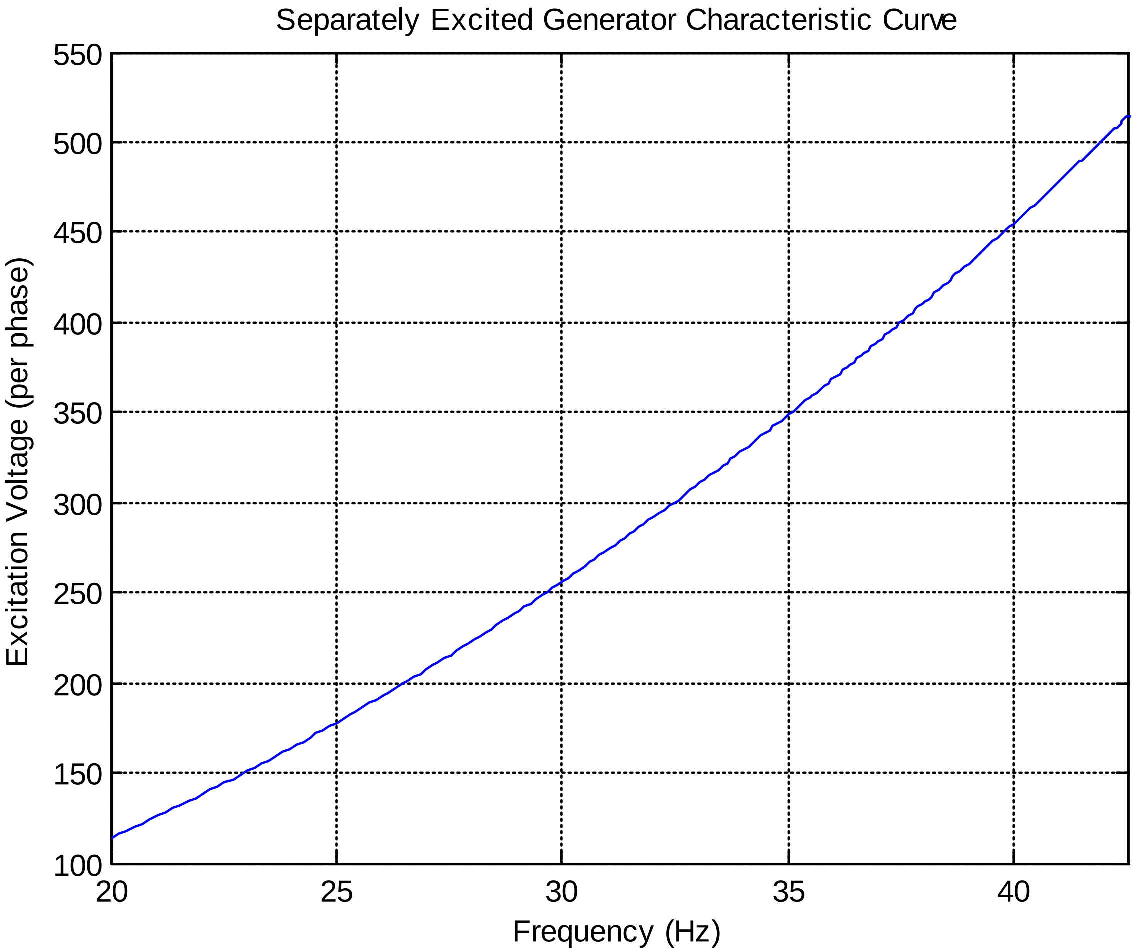


Figure 6: Voltage-Frequency Curve for a Separately Excited Generator

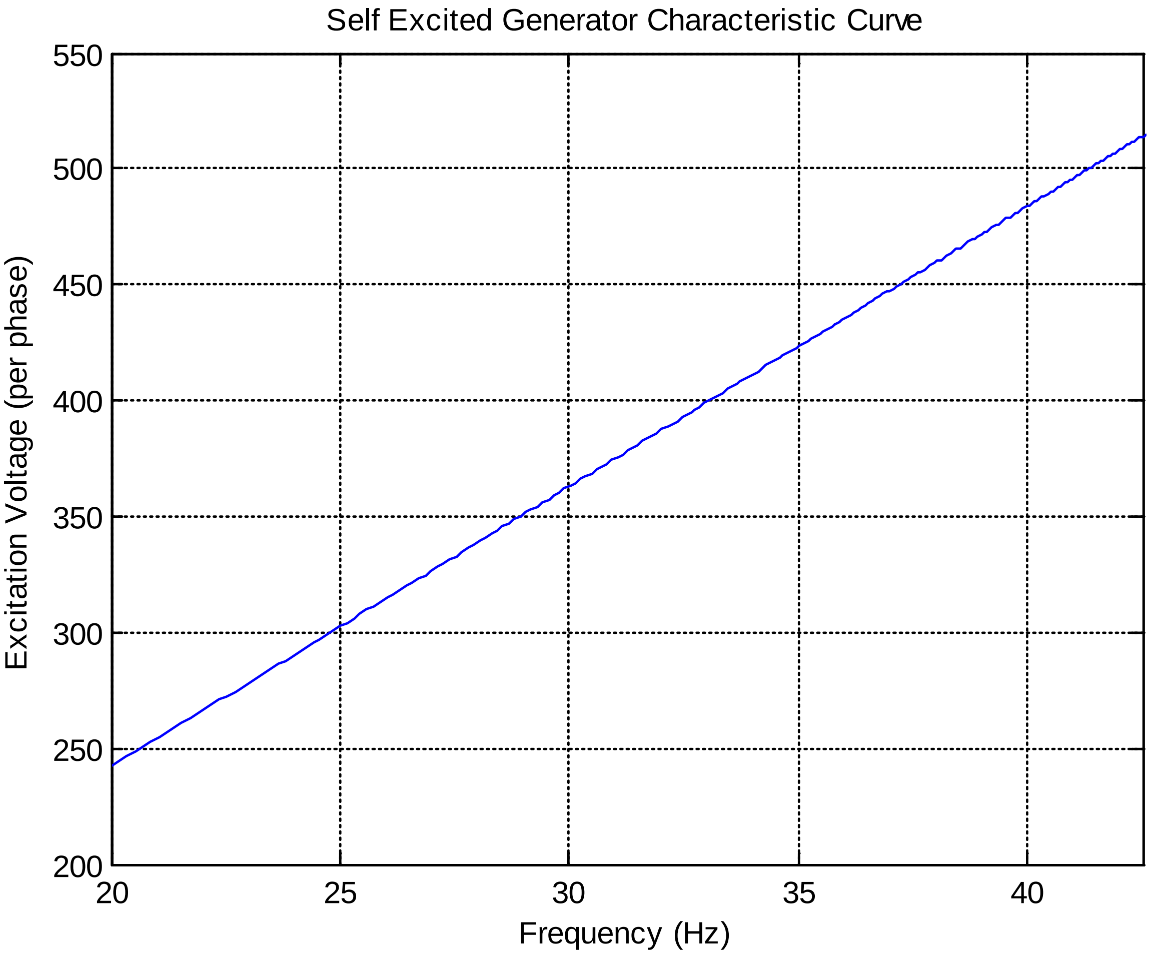


Figure 7: Voltage-Frequency Curve for a Self Excited Generator

The Induction Motor

Accurately modeling the induction model is an integral part of getting a useful and valid result. The requirements of the induction motor are based solely on the power requirement of the centrifugal pump that is to be discussed momentarily. The pump that is selected for this simulation requires approximately 20 hp at the operating point, which is at 2900 rpm. Based upon typical induction motor efficiencies, the induction motor will need to be a roughly 22 hp 2-pole motor. In order to accurately model this motor, the induction motor parameters were selected accordingly to yield the torque-speed curve of the motor as shown in Figure 8, ensuring that the motor operates at the desired power output at the operating point of 2900 rpm. The above mentioned parameters that were selected were based upon the common induction motor per-phase equivalent circuit as shown in Figure 9. Although the problem to be solved is not a steady state case, the mechanical time constants are significantly greater than the electrical time constants, thus sinusoidal steady state modeling of the induction motor is justified.

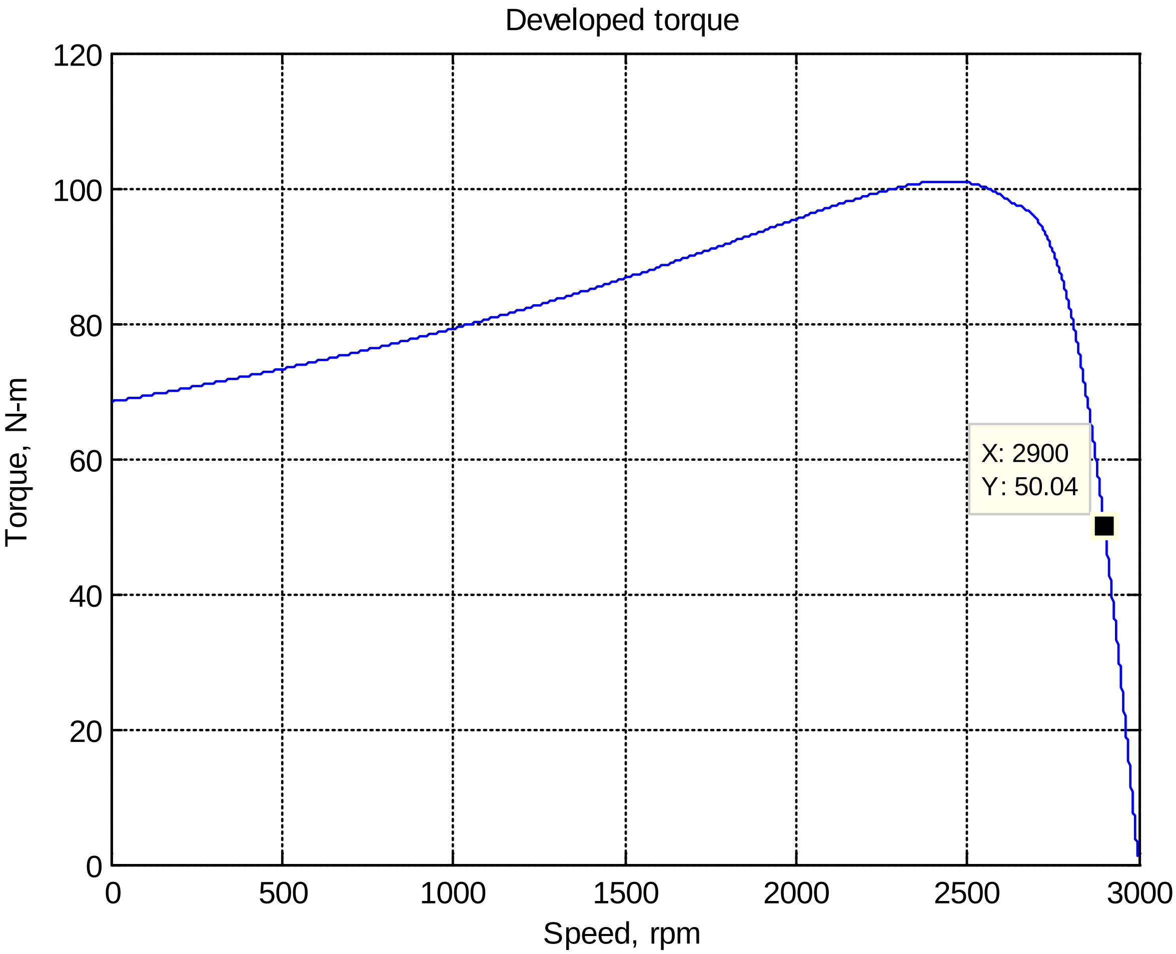


Figure 8: Torque-Speed Curve for the Induction Motor

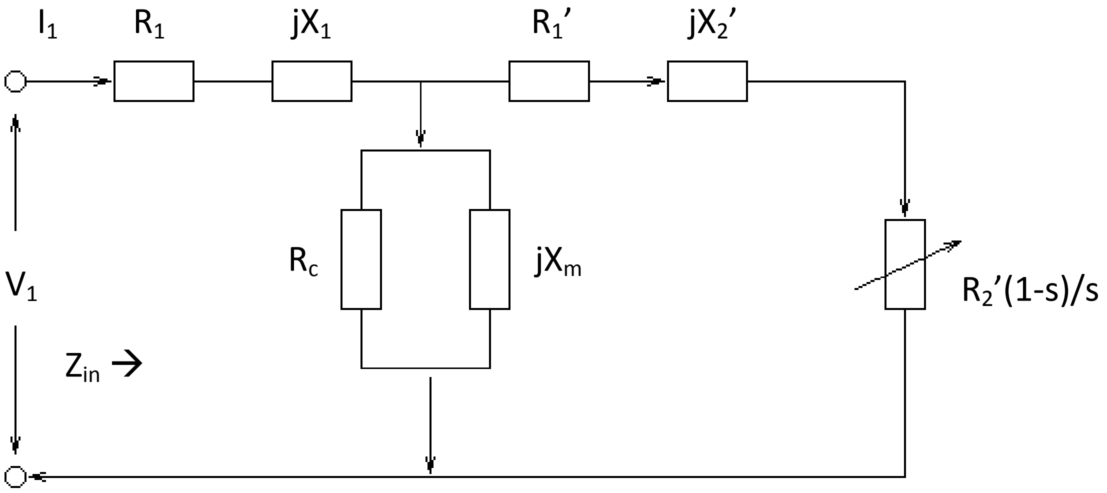


Figure 9: Per Phase Induction Motor Equivalent Circuit

The following rated frequency parameters were used in the induction motor model:

$R_1 = 0.117\Omega$

$R_2{}' = 1.49\Omega$

$X_1 = 1.52\Omega$

$X_2{}' = 1.58\Omega$

$R_c = 386\Omega$

$X_m = 32.29\Omega$

Additionally, since much of this study occurs at less than the rated speed, it is important use empirical induction motor data to correct the curve to more accurately portray the characteristics of this motor at low speeds. In order adjust for the responses of the resistance and leakage inductance at lower frequencies, a heuristic approach [2] is incorporated into the model that accounts for the skin (or deep bar) effects.

During the operation of induction motors, there are unavoidable losses in power attributed to friction and windage ($P_{F\&W}$). In this simulation, the friction and windage losses of the induction motor is set to 700W, which falls within the typical range of 3-5% of the total power consumed by the motor. Once that number was determined, the amount of torque due to friction and windage ($T_{F\&W}$) can be calculated using the following formula.

$$T_{F\&W} = \frac{P_{F\&W}}{\frac{\pi}{30} * 2900} \tag{6}$$

Where

2900 is the steady state operating speed in revolutions per minute and

s is slip and is defined as

$$s = \frac{n_{sync\,hronous} - n_{motor}}{n_{sync\,hronous}} \tag{7}$$

Using the circuit in Figure 9, the following formulae can be applied to give several meaningful results including current into the motor (I_1), power factor of the motor (PF), real power into the motor ($P_{in,motor}$), apparent power into the motor ($S_{in,motor}$), total developed torque (T_D), and the torque output from the motor (T_{out}).

$$I_1 = \frac{V_1}{Z_{in}} \tag{8}$$

$$PF = \cos\big(angle(V_1) - angle(I_1)\big) \tag{9}$$

$$P_{in,motor} = 3 * V_1 * I_1 * PF \tag{10}$$

$$S_{in,motor} = \frac{P_{in,motor}}{PF} \tag{11}$$

$$T_D = \frac{3 * poles * (I_2')^2 * R_2'}{4 * \pi * s * f} \tag{12}$$

$$T_{out} = T_D - T_{F\&W} \tag{13}$$

The input parameters for the induction motor part of the model are the voltage and frequency output by the generator, as well as the current shaft speed of the motor. Using these inputs, the model is able to compute the current that is drawn by the motor, the total real and apparent power required by the motor, as well as the total developed torque of the motor that is output to the centrifugal pump.

The Centrifugal Pump

The first step in modeling the centrifugal pump is to find appropriate parameters from which we can accurately model its performance. The primary requirement of this pump is that it must produce a minimum of 120 meters of head. This is assuming the situation discussed involves pumping water from 80 meters below the surface to a water tower that stands 40 meters tall. You will find the pump upon which the model is based in the Appendix. The pump in this model is given a load torque requirement that is typical for a centrifugal pump [3]. The shape of the curve is parabolic in nature and begins with a torque requirement of 15% of the full load torque. From there, it decreases to 10% of the full load torque at 20% of the rated full speed and then increases proportional to speed squared until reaching its operating point. The speed torque curve for the centrifugal pump is shown in Figure 10. As is evident by the curve, the pump has an initial torque requirement at 6.3 Nm. From there, it decreases to 4.2 Nm at 580 rpm before growing quadratically toward the operating point of 2900 rpm where the load is 42 Nm.

The input parameters for the pump part of the model are the total developed torque and the shaft speed of the motor. In each iteration of the model, it ascertains that the load torque of the pump is met or exceeded by the total developed torque supplied by the induction motor.

The next step is calculating the change in speed that is accounted for by the difference in the load torque of the pump and the developed torque that is supplied to the pump. The difference results in an accelerating torque, which drives the system to run at a higher speed. Computing the change in speed $\frac{d\omega_m}{dt}$ is achieved by solving the following differential equation:

$$T_D = J\frac{d\omega_m}{dt} + T_L + \beta\omega_m \tag{14}$$

where T_D,T_L,and ω_m are given from earlier parts of the simulation. The last term, $\beta\omega_m$, is the losses due to friction and windage within the pump and motor. The moment of inertia can be calculated using the following empirical formula [4] that

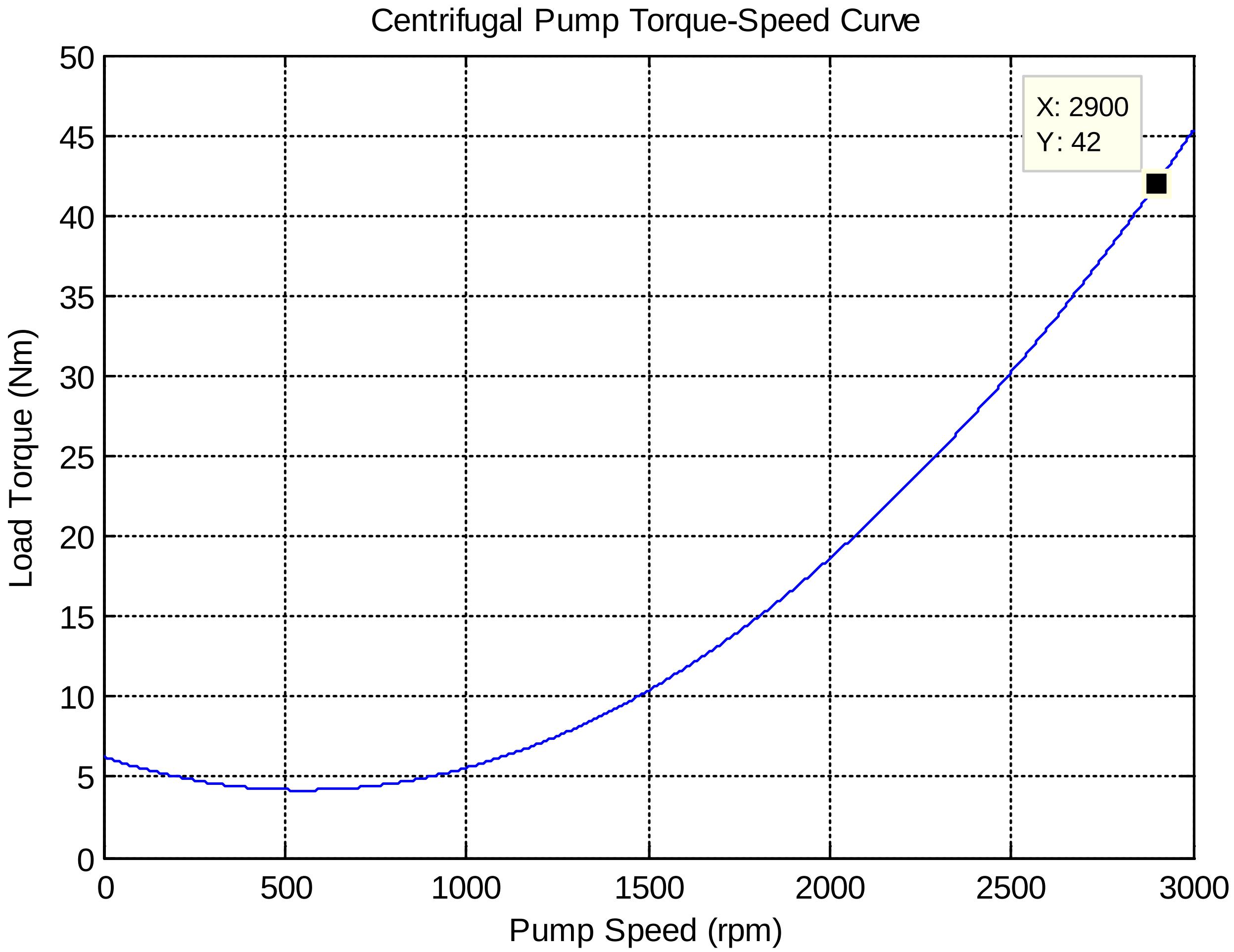


Figure 10: Load Torque-Speed Curve for the Centrifugal Pump

determines the moments of inertia individually for the pump and the induction motor, and then combines them to form the moment of inertia for the system.

$$J_{pump} = 0.03768 \left(\frac{P}{N}\right)^{0.9556} \tag{15}$$

$$J_{motor} = 0.0043 \left(\frac{P}{N}\right)^{1.48} \tag{16}$$

$$J = J_{pump} + J_{motor} \tag{17}$$

Where

P is the mechanical power in kW

N is the pump speed in thousands of rpm

For the case being studied in this paper, the resulting moment of inertia for the motor-pump combination is

$$J = 0.1547 kg \cdot m^2$$

As the developed torque (T_D) exceeds the load torque(T_L), there will be an acceleration of the pump. The increase in speed will occur until equilibrium is reached between the load torque and the total developed torque, which implies that the accelerating torque is zero and the stable operating point of the system has been reached. In this setup of the system, that equilibrium is achieved at approximately 2900 rpm. The output of the centrifugal pump portion of the model is the new shaft speed, which is based upon the solved differential equation in equation (12). This result is used in the following iteration of the model.

The Parallel Load

A critical variable in this problem that is being explored is the load on the system that does not stem from the motor-pump. This proportion of the system power will be dedicated to running common loads such as receptacles and ceiling fans in parallel with the motor and will have a direct correlation with the usefulness of this technique. As the motor load becomes a larger part of the overall system, the advantage of the proposed technique will become more evident. In the model, the parallel load will be set to various levels to provide analysis for the broad applicability of the technique. For the setup in this paper, the power factor of the parallel load is 0.85, but this can easily be changed to fit a specific situation.

All of the above modules are run, one increment at a time, for the duration of the desired time span to be tested. Obviously, the time period that is interesting in this situation is the time that it takes for the generator and the motor-pump combination to reach their stable operating points. The model is one that will be used to test a variety of different setups to explore and define the situations in which the technique is the most relevant and useful.

Chapter 4: Presentation of the Results

Several different configurations were simulated using the model outlined in the previous section. There are three primary setups that will be analyzed in this study. The first two are those that power a 20 hp pump with parallel loads of 45 kW and 10 kW, both with a 0.85 power factor. The third setup will only power the motor load. Cases I and II represent systems where the steady state load of the pump motor is roughly 25% and 60% of the total system steady state load, respectively, with the rack pulled back to the point that allows the system to begin with the generator at 40% of synchronous speed. Following those tests, further results from a broad range of situations will be explored to draw a more generalized and robustly applicable result.

Case I: 20 hp pump with a 45 kW parallel load

From the system simulation, there are several results of interest. The purpose of this paper is to illustrate the improvement of this technique against a full voltage and frequency start of the system. Where applicable, the plot of the system using the novel technique discussed here as well as the system without use of the technique will be superimposed on the same axes in order to show the overall improvement in system performance. Figures 11-17 show the excitation and terminal voltages, motor current , motor speed, parallel load average and apparent power requirements, motor average power input and motor apparent power input, respectively, for Case I. Figures 18 and 19 display, respectively the total average and apparent power required by both the motor and the 45 kW parallel load.

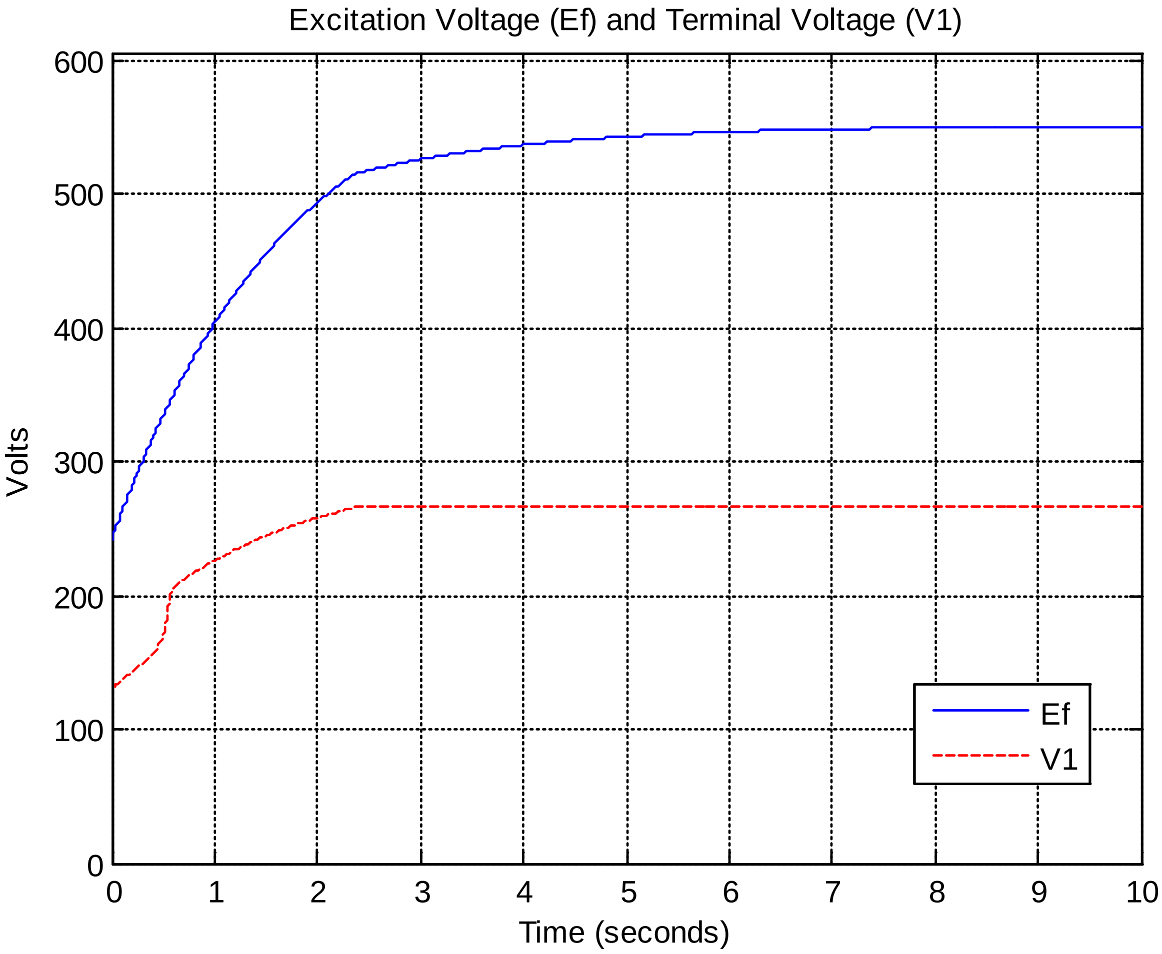


Figure 11: Case I – Excitation and Terminal Voltages

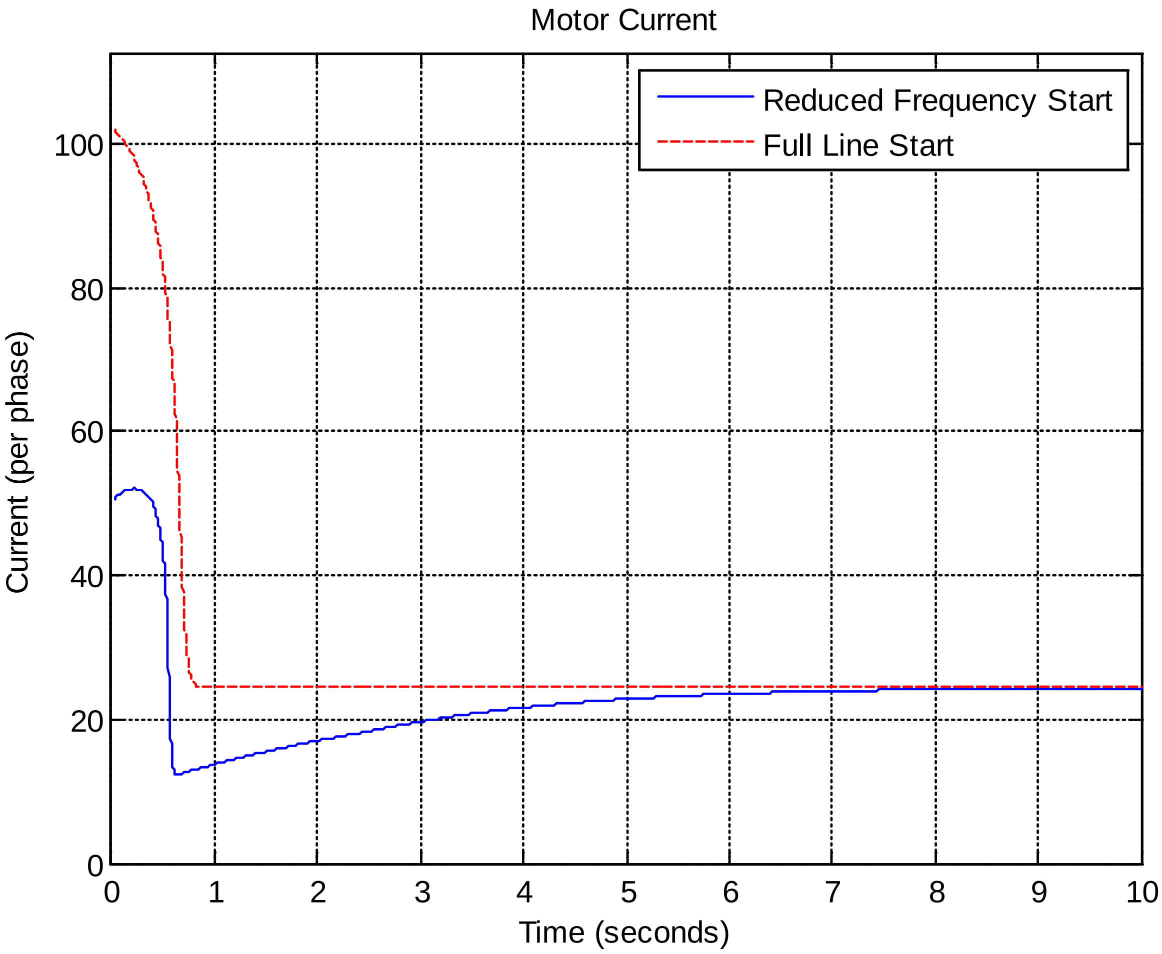


Figure 12: Case I - Current into the Motor

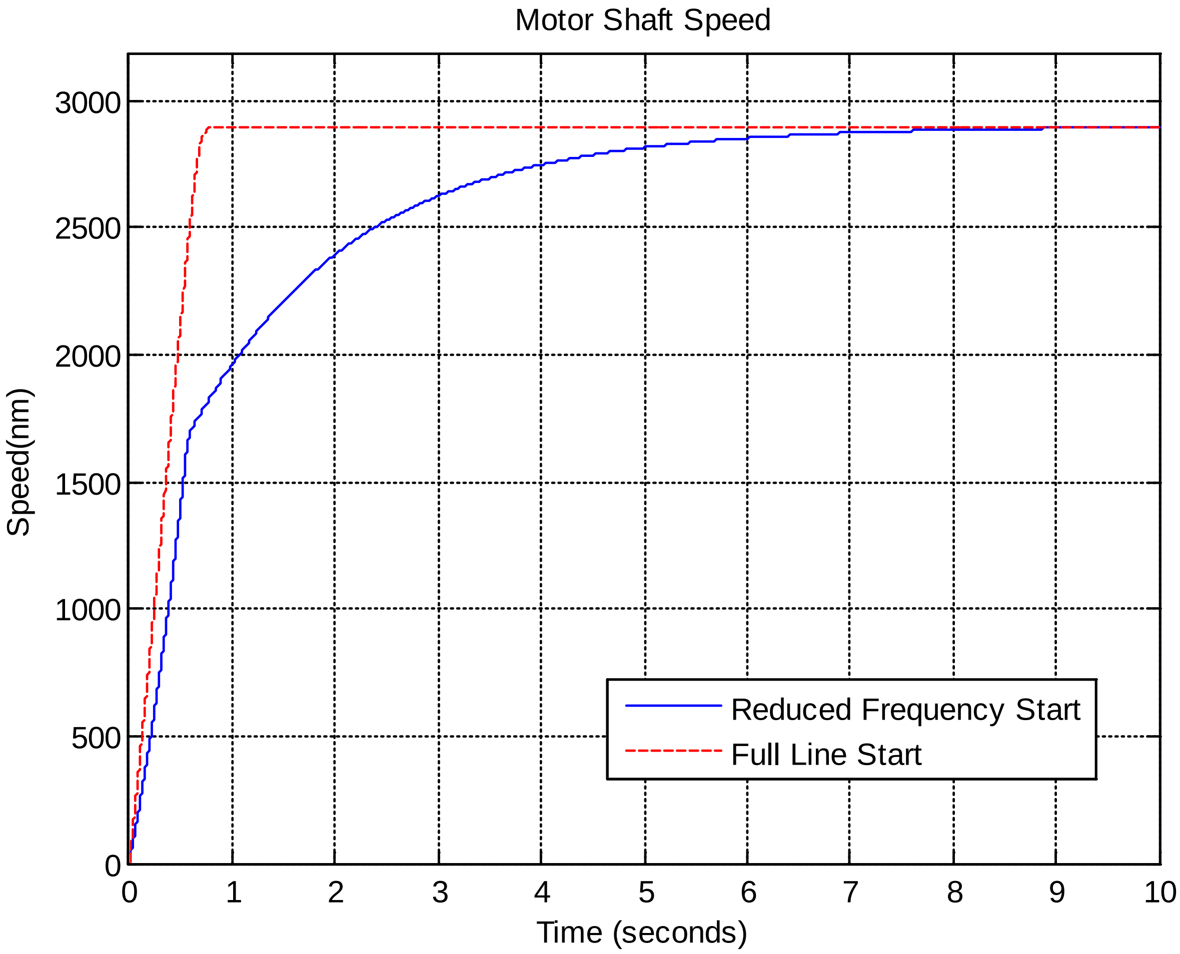


Figure 13: Case I - Motor Shaft Speed

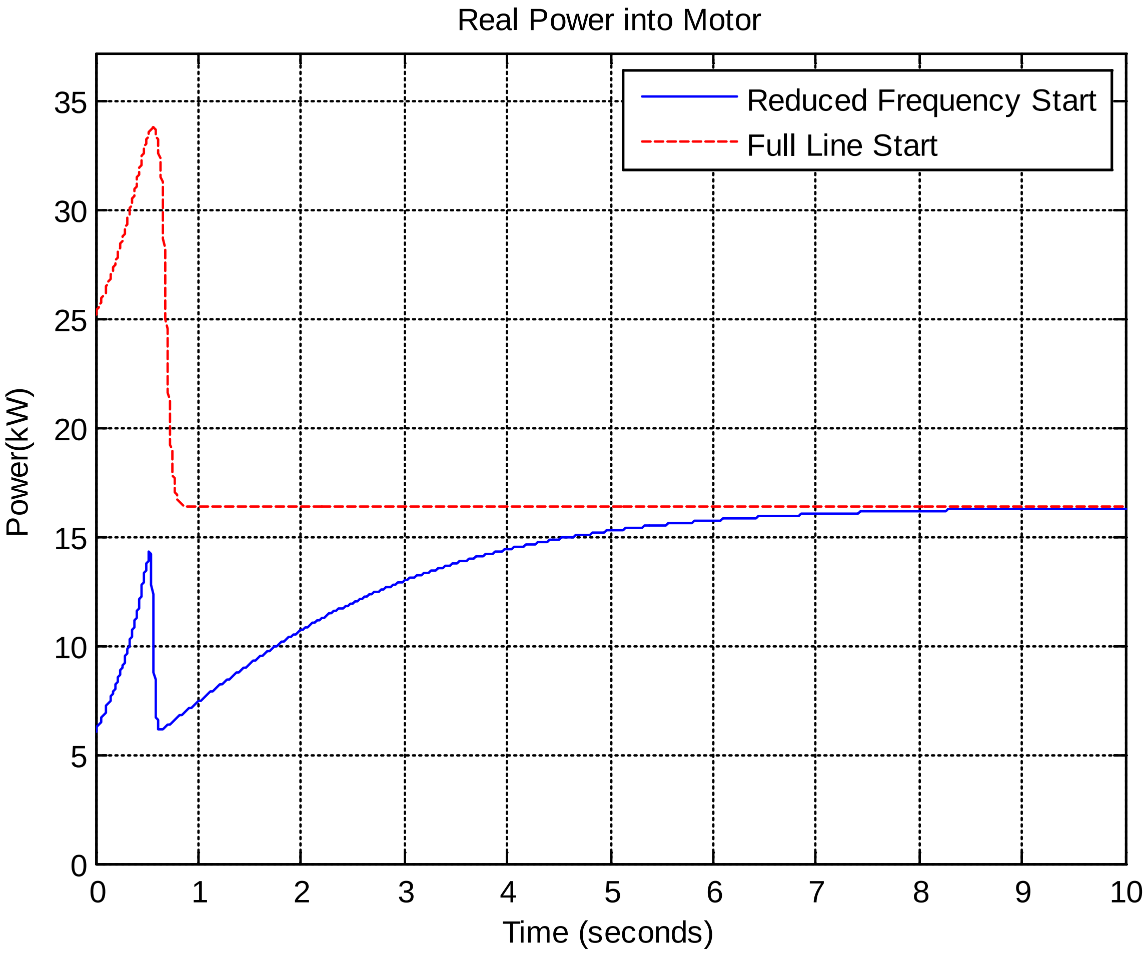


Figure 14: Case I - Real Power into the Motor

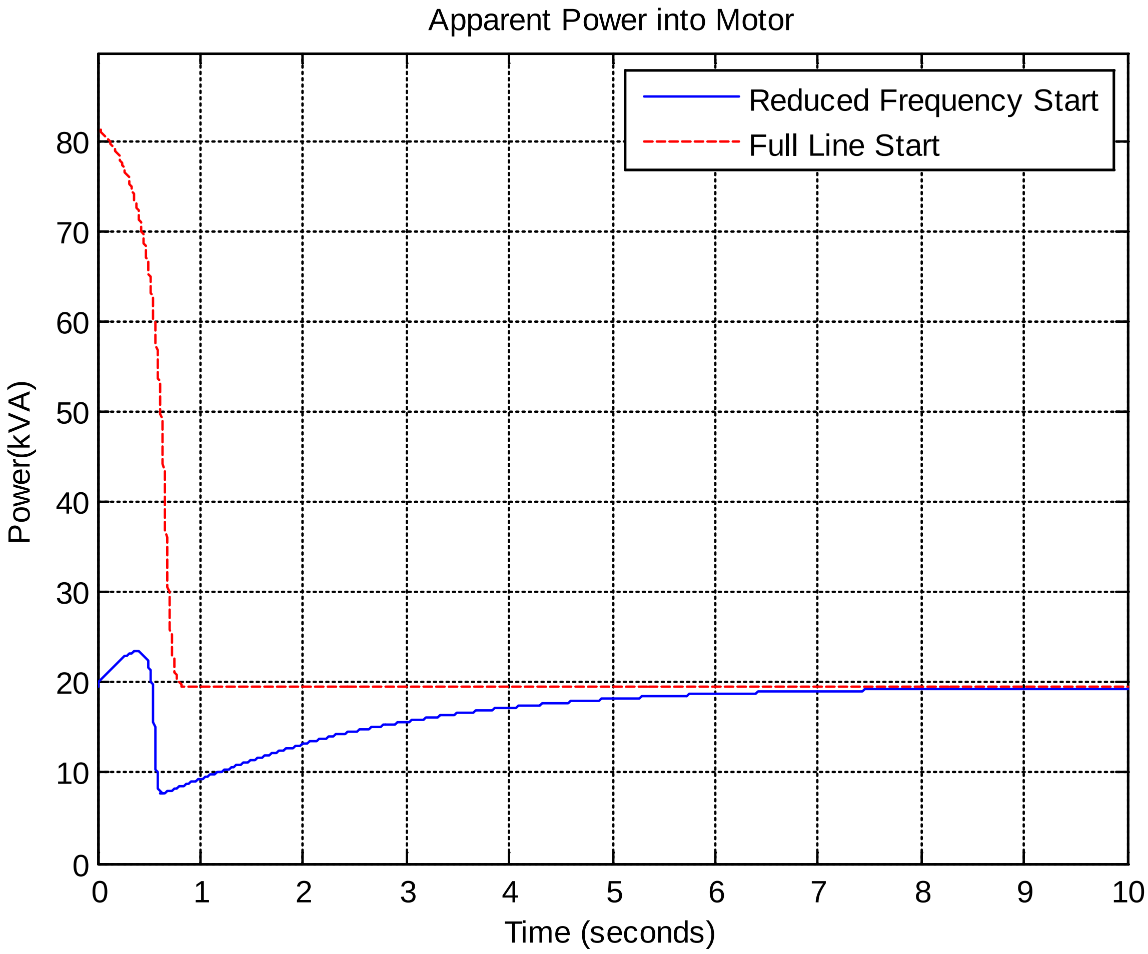


Figure 15: Case I - Apparent Power into the Motor

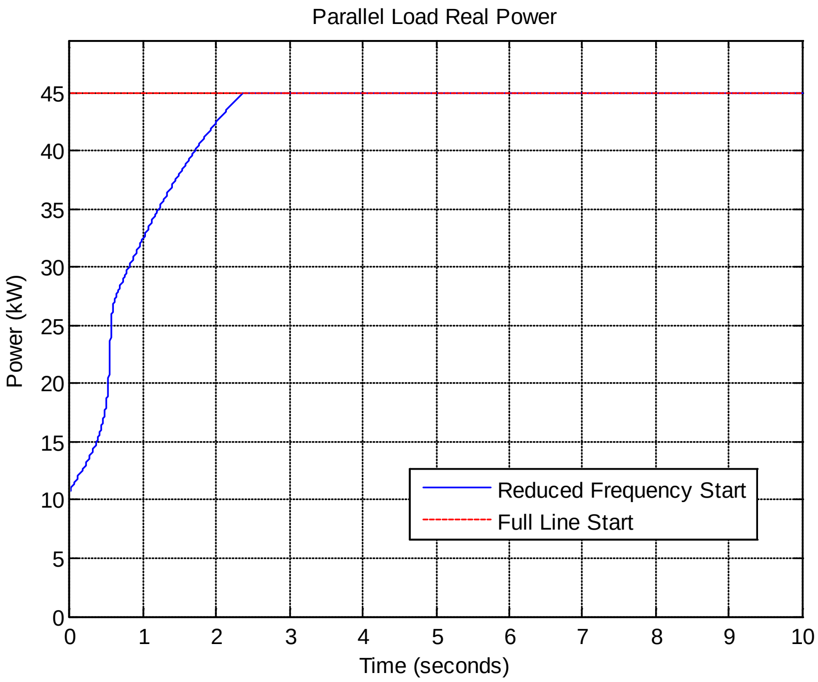


Figure 16: Case I – 45 kW Parallel Load Real Power

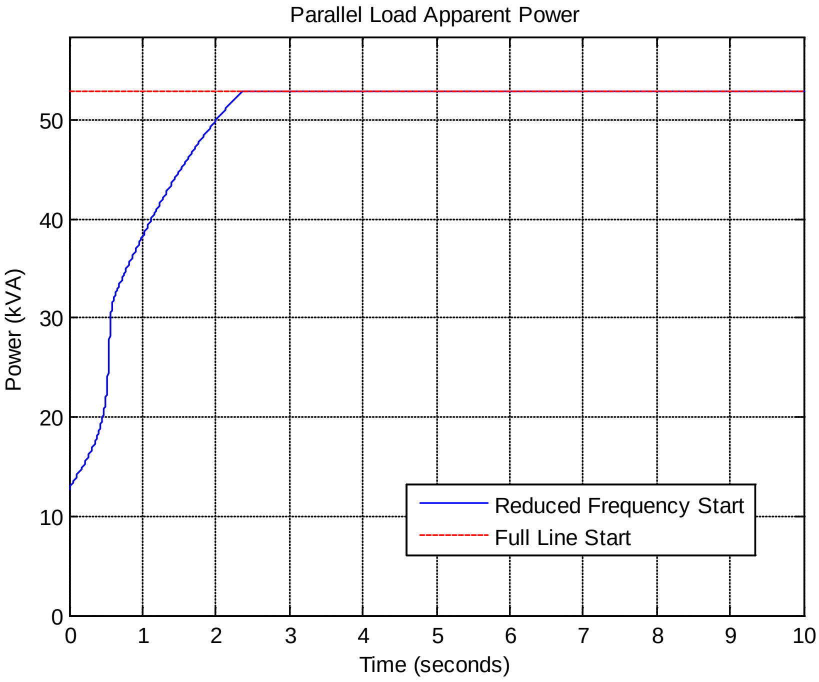


Figure 17: Case I – 45 kW Parallel Load Apparent Power

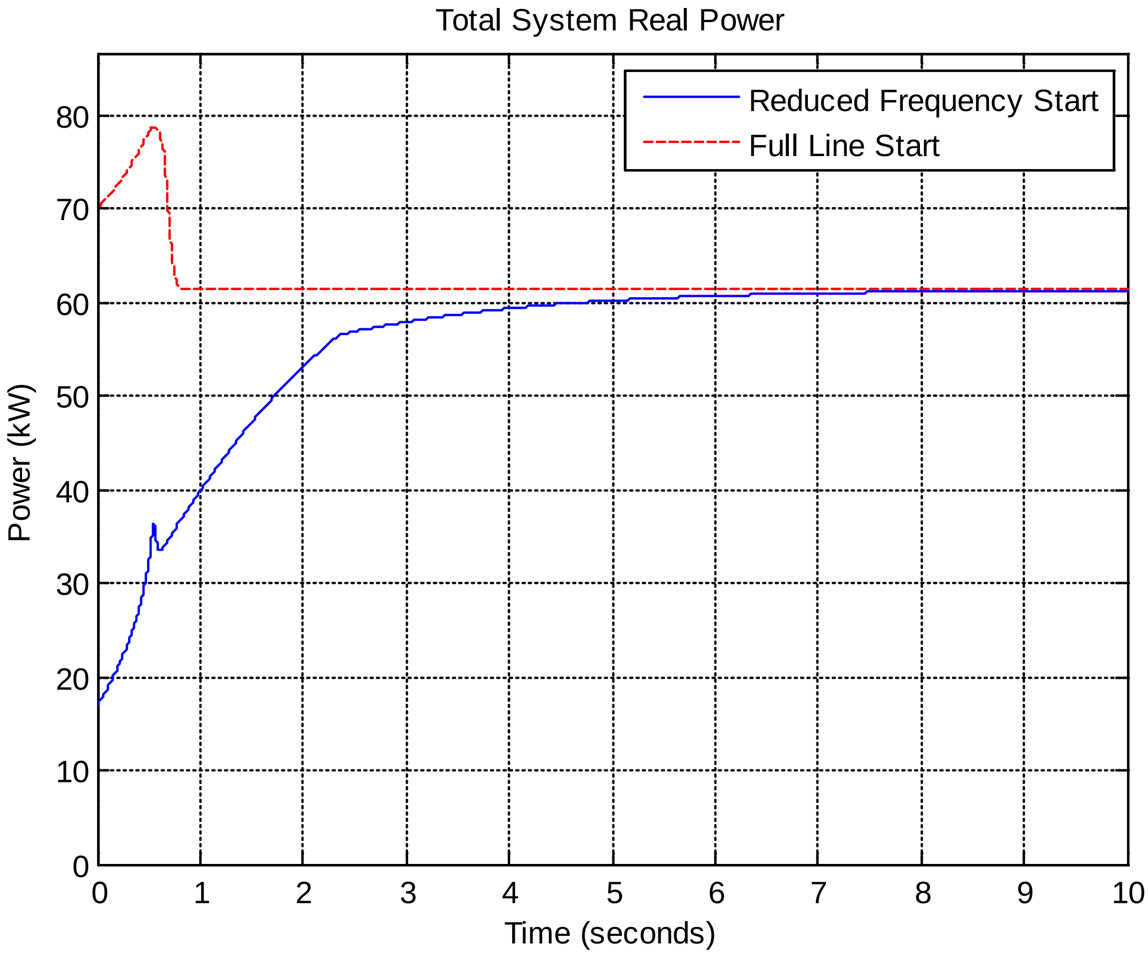


Figure 18: Case I – Total System Real Power

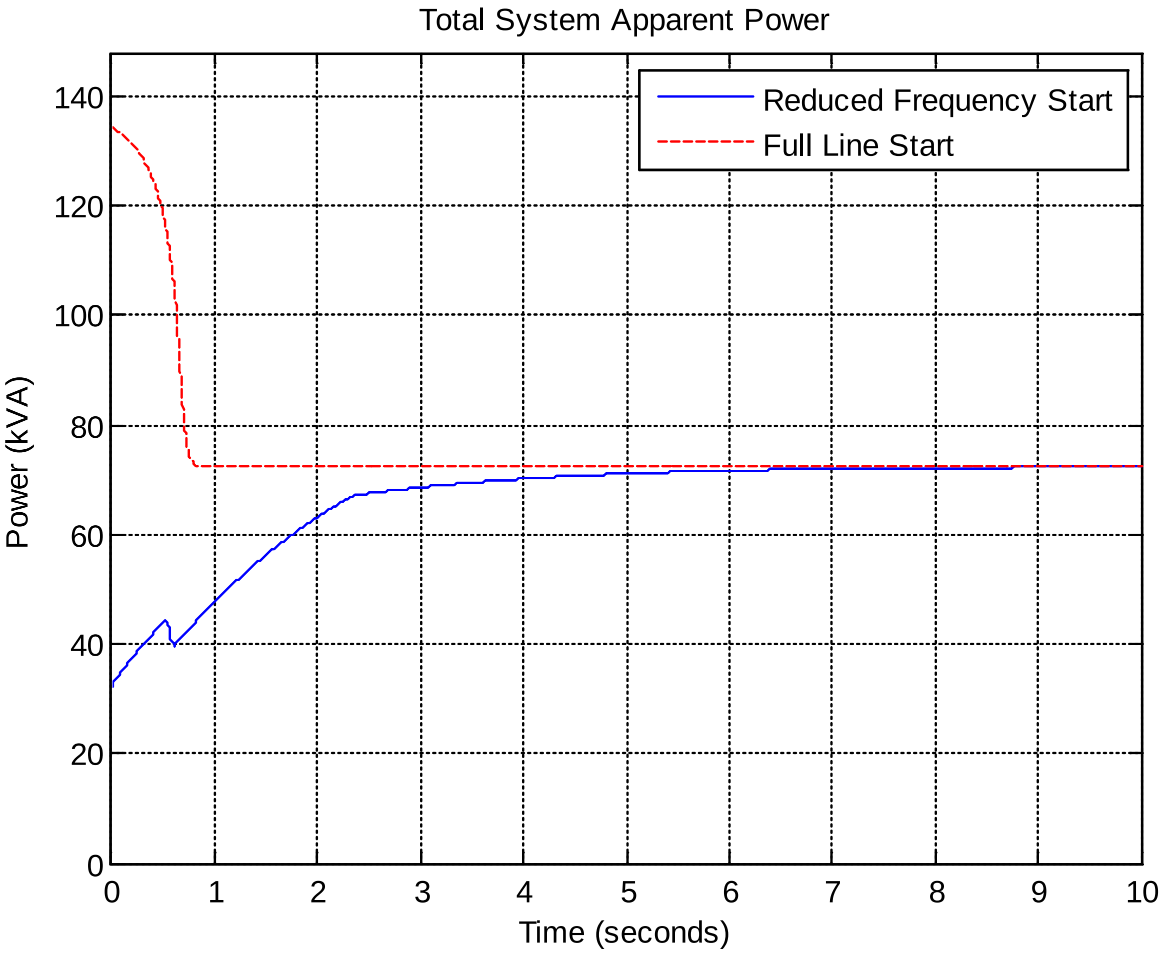


Figure 19: Case I – Total System Apparent Power

The plot of most significance in this simulation is presented in Figure 19 which shows the total system apparent power demanded by the combination of the motor load as well as the 45 kW parallel load at 0.85 power factor. As is evident from the plot, there are significant savings in the power requirement of the system when use the technique outlined in this paper. More specifically, with a full line start, the maximum apparent power requirement of the system peaks at 134.54 kVA. When using the reduced frequency technique, the maximum apparent power requirement is 72.39 kVA. In this case, the required apparent power supplied is reduced by 62.15 kVA, or 46%.

Case II: 20 hp pump with a 10 kW parallel load

The same logic and parameters were used when examining the case where the parallel load was 10 kW with 0.85 power factor. Figures 20-26 show the excitation and terminal voltages, motor current , motor speed, parallel load average and apparent power requirements, motor average power input and motor apparent power input, respectively, for Case I. Figures 27 and 28 display, respectively the total average and apparent power required by both the motor and the 10 kW parallel load with Figure 28 being the plot of most significance in this simulation. There are significant savings in the power requirement of the system when use the technique outlined in this paper. More specifically, with a full line start, the maximum apparent power requirement of the system peaks at 93.37 kVA. When using the reduced frequency technique, the maximum apparent power requirement is 38.45 kVA. In this case, the required apparent power supplied is reduced 59%.

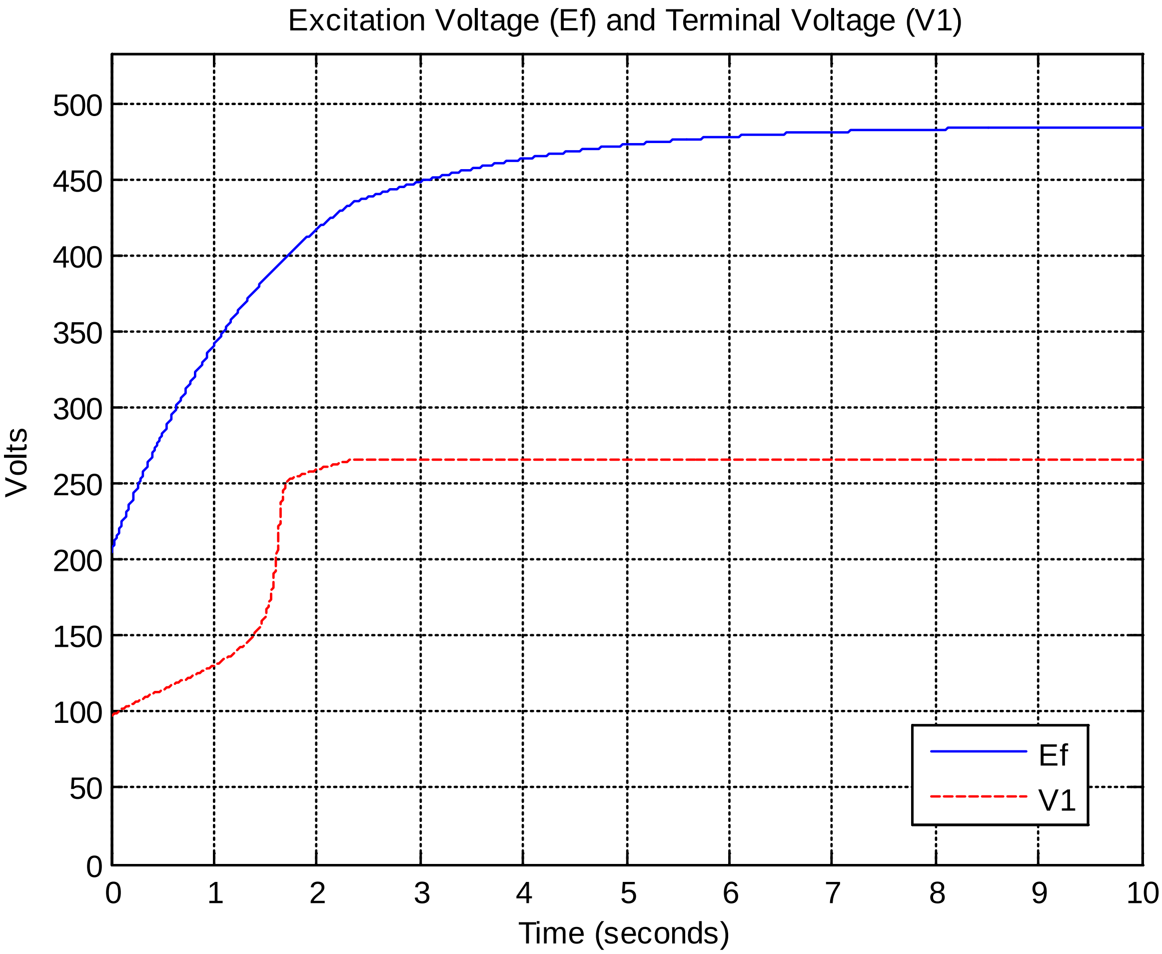


Figure 20: Case II – Excitation and Terminal Voltages

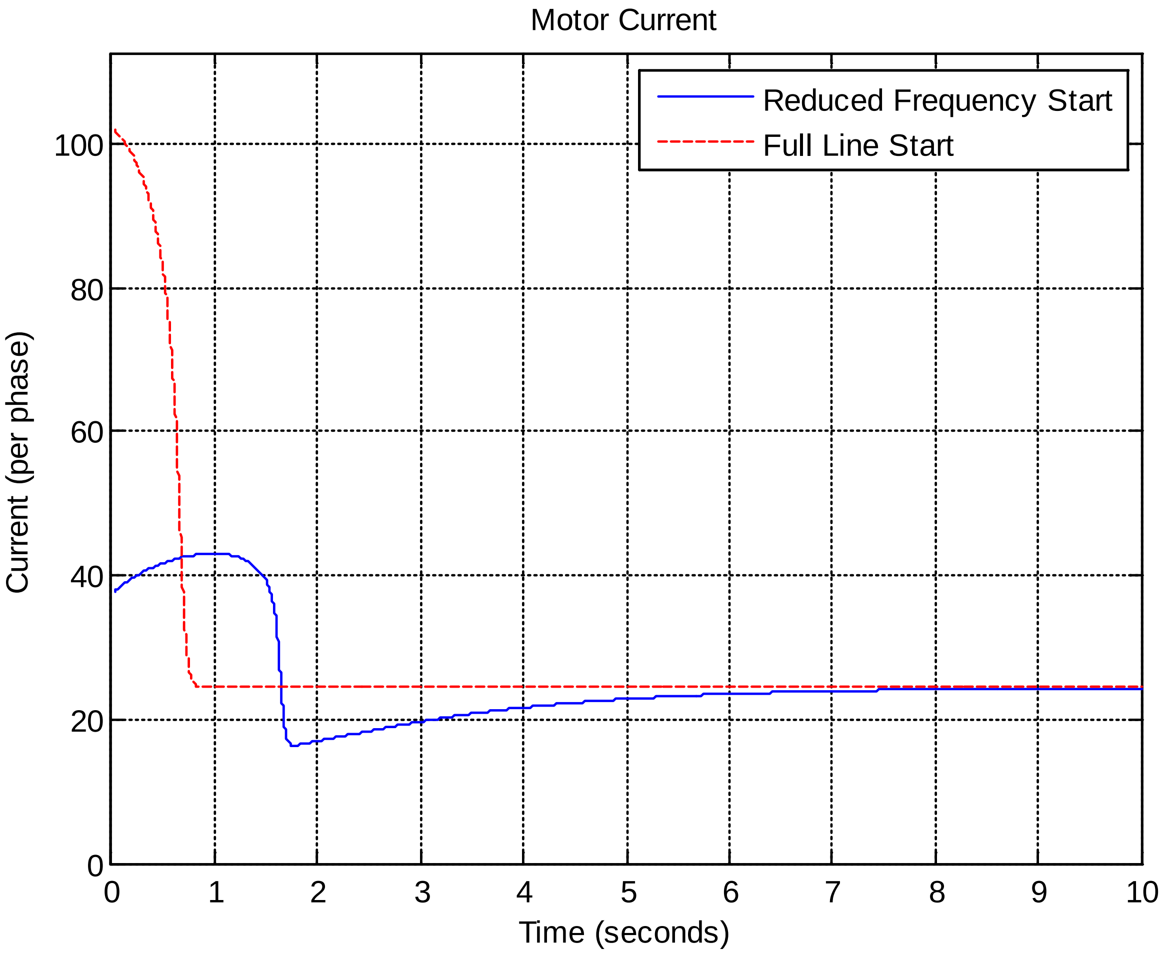


Figure 21: Case II - Current into the Motor

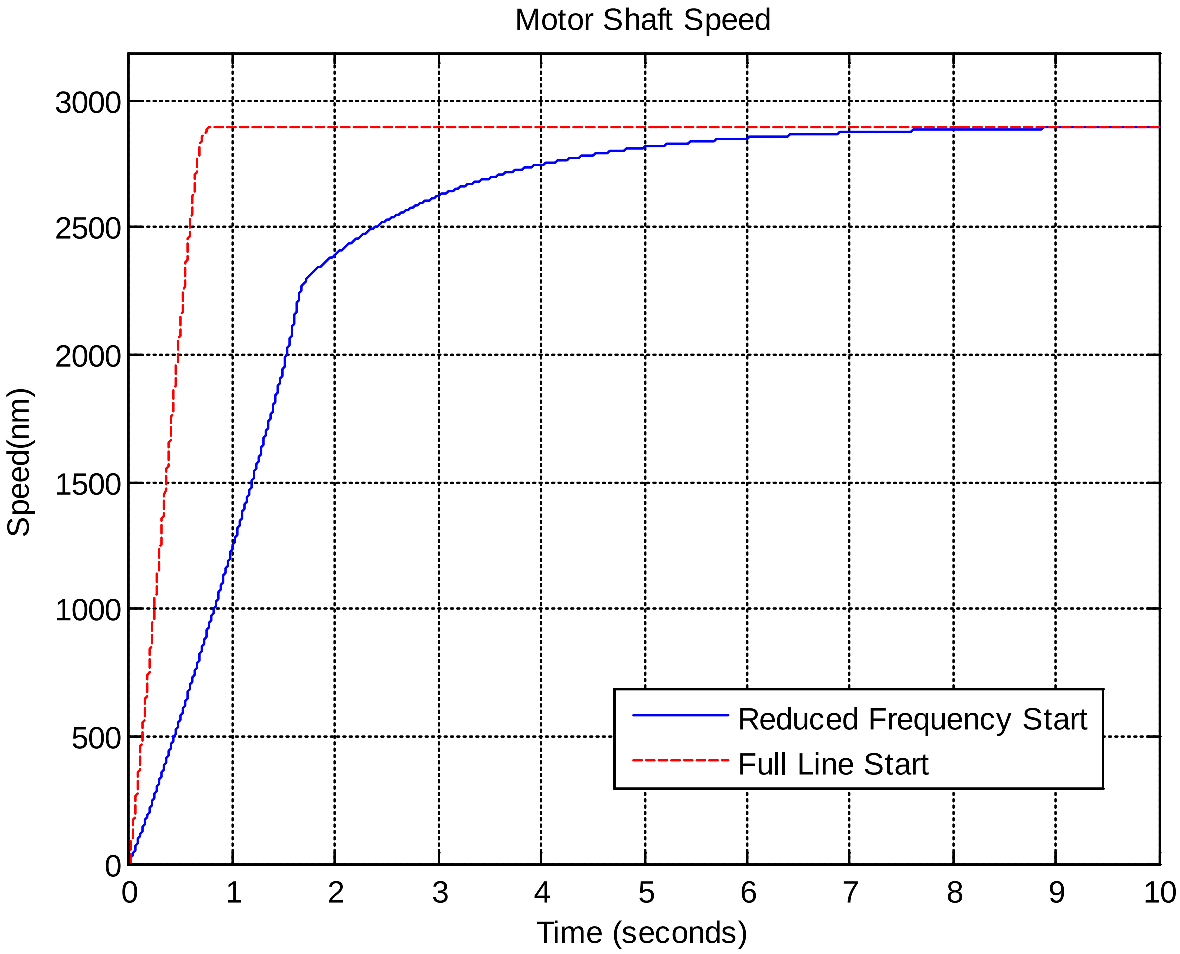


Figure 22: Case II - Motor Shaft Speed

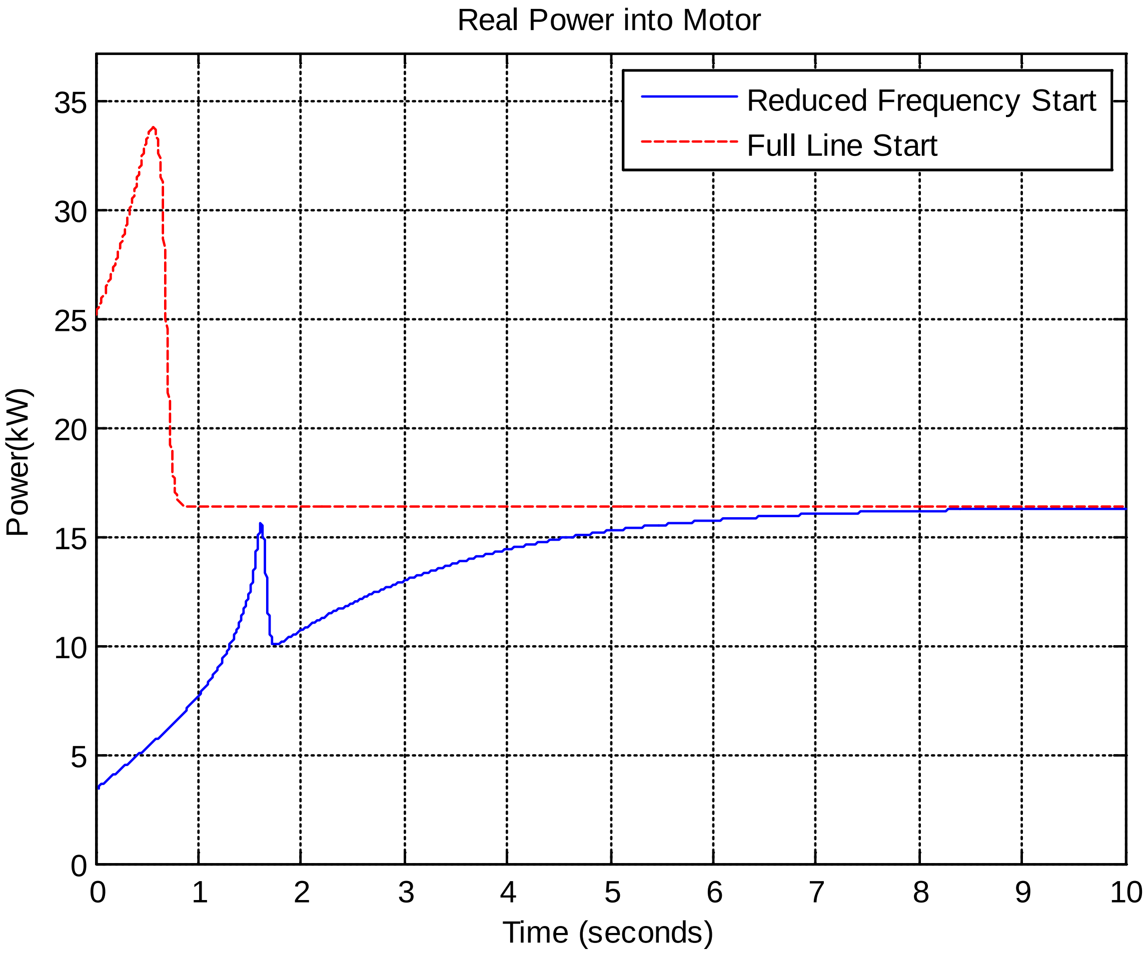


Figure 23: Case II – Real Power into the Motor

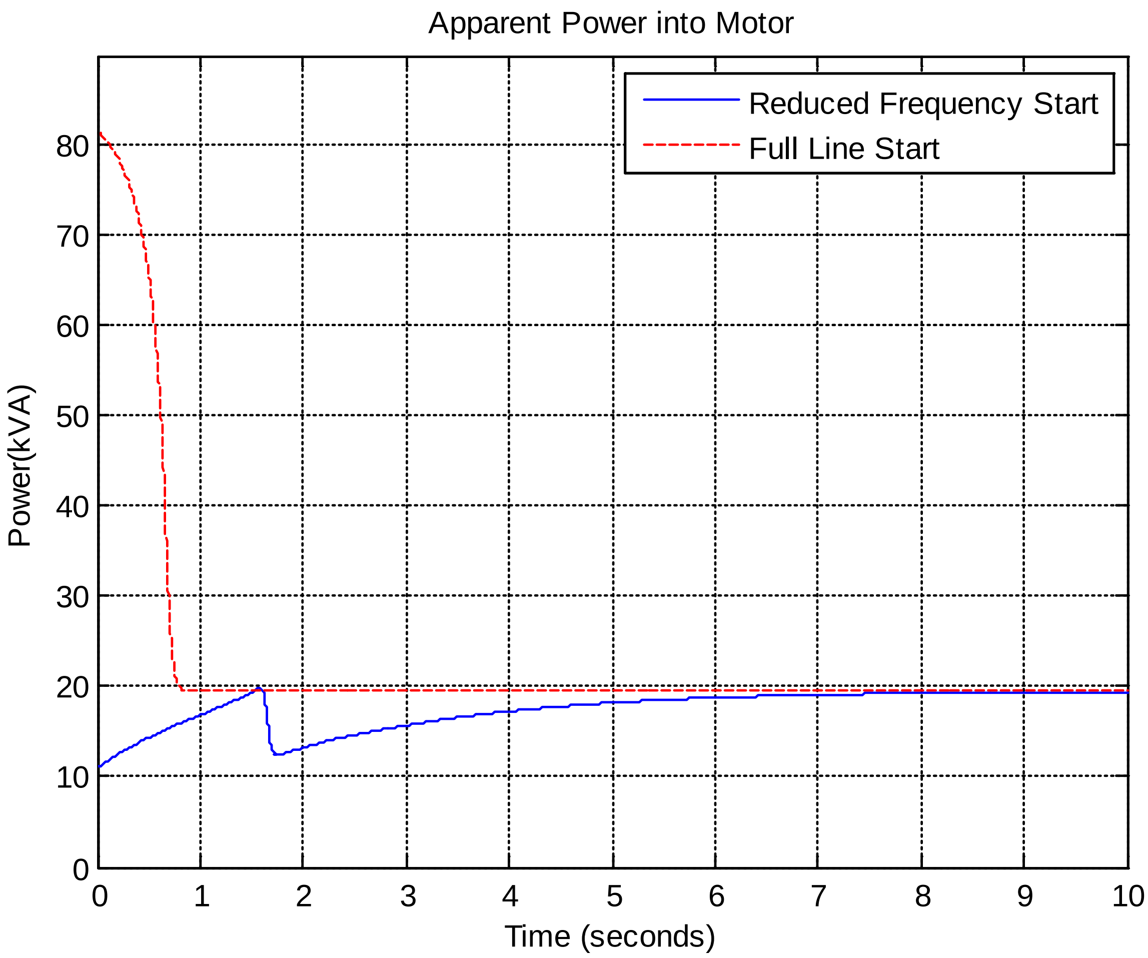


Figure 24: Case II – Apparent Power into the Motor

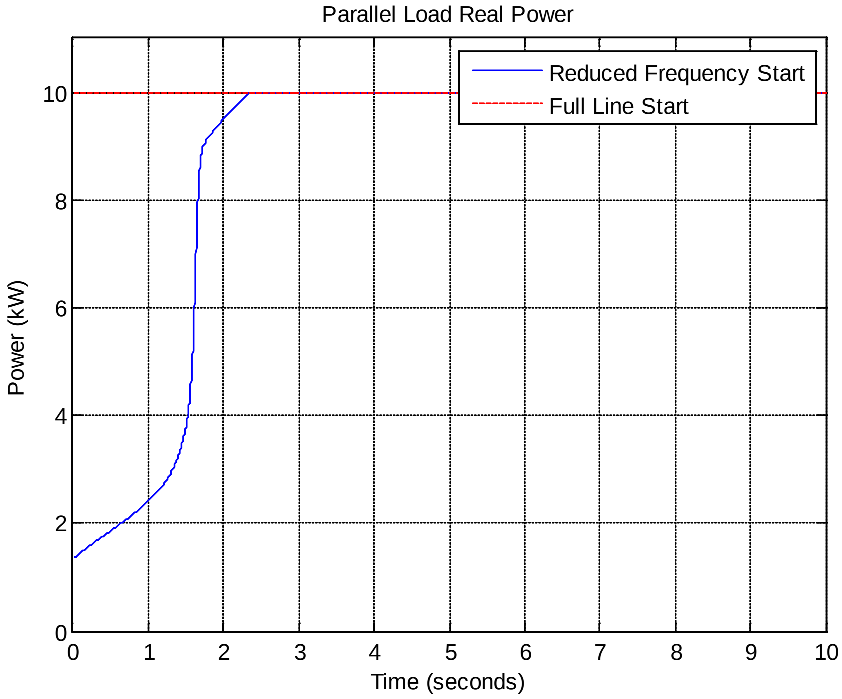


Figure 25: Case II – 10 kW Parallel Load Real Power

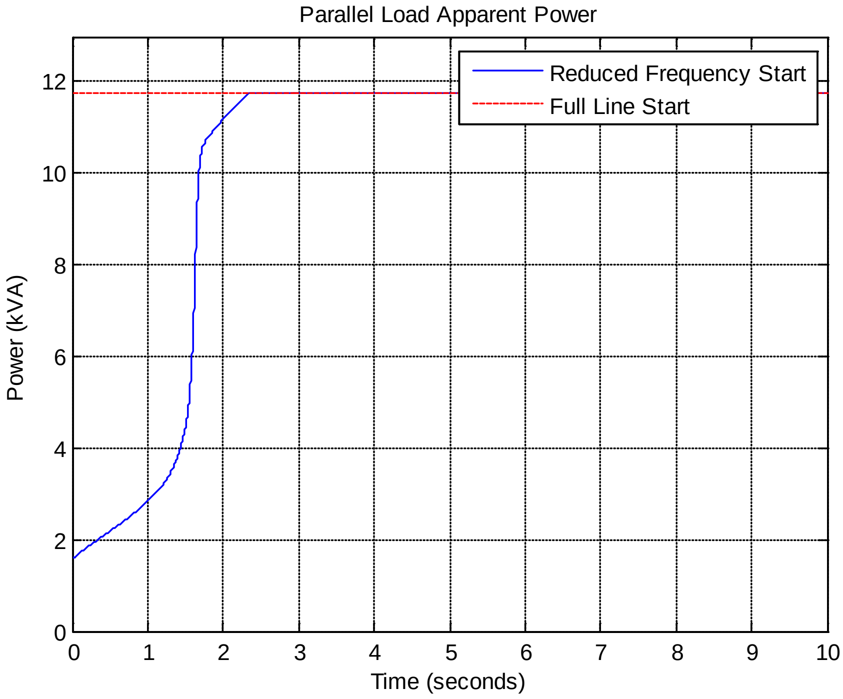


Figure 26: Case II – 10 kW Parallel Load Apparent Power

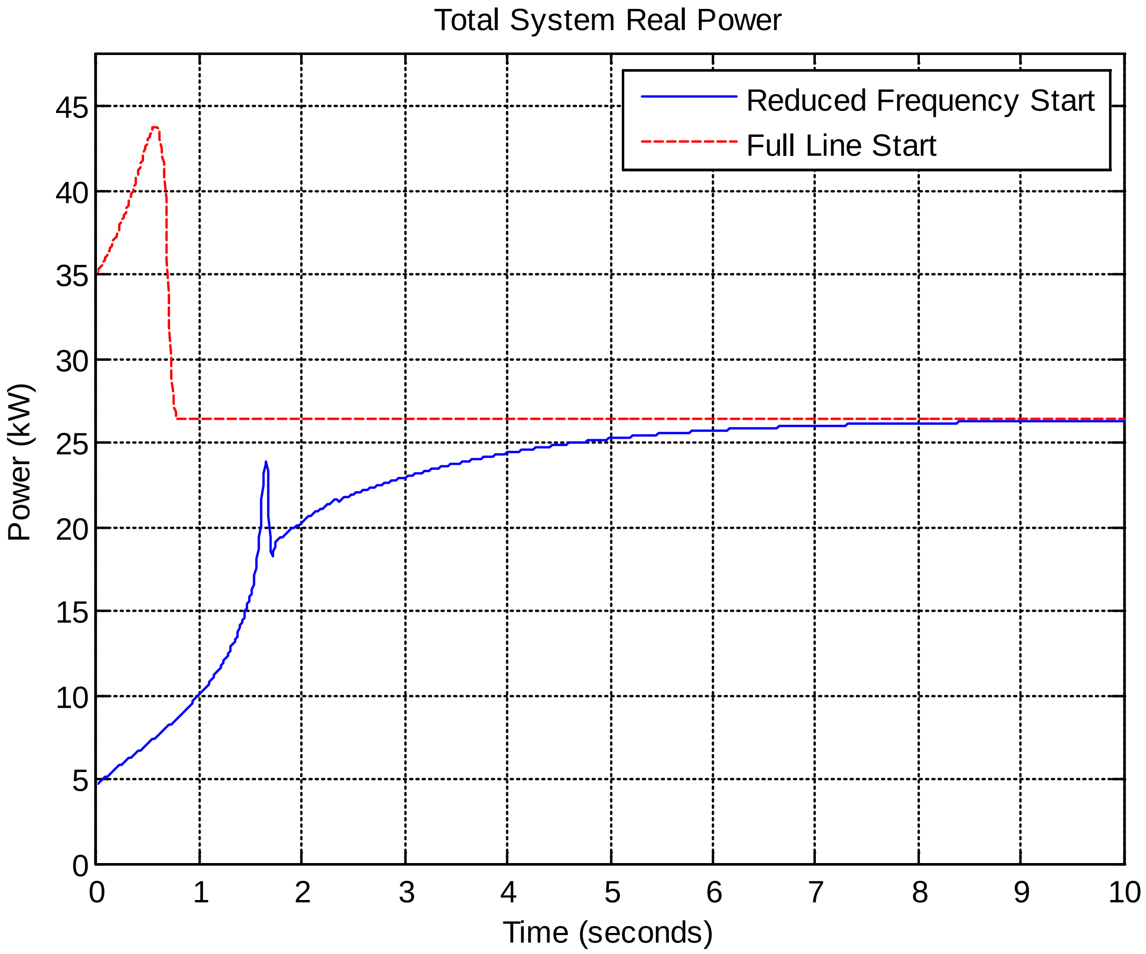


Figure 27: Case II – Total System Real Power

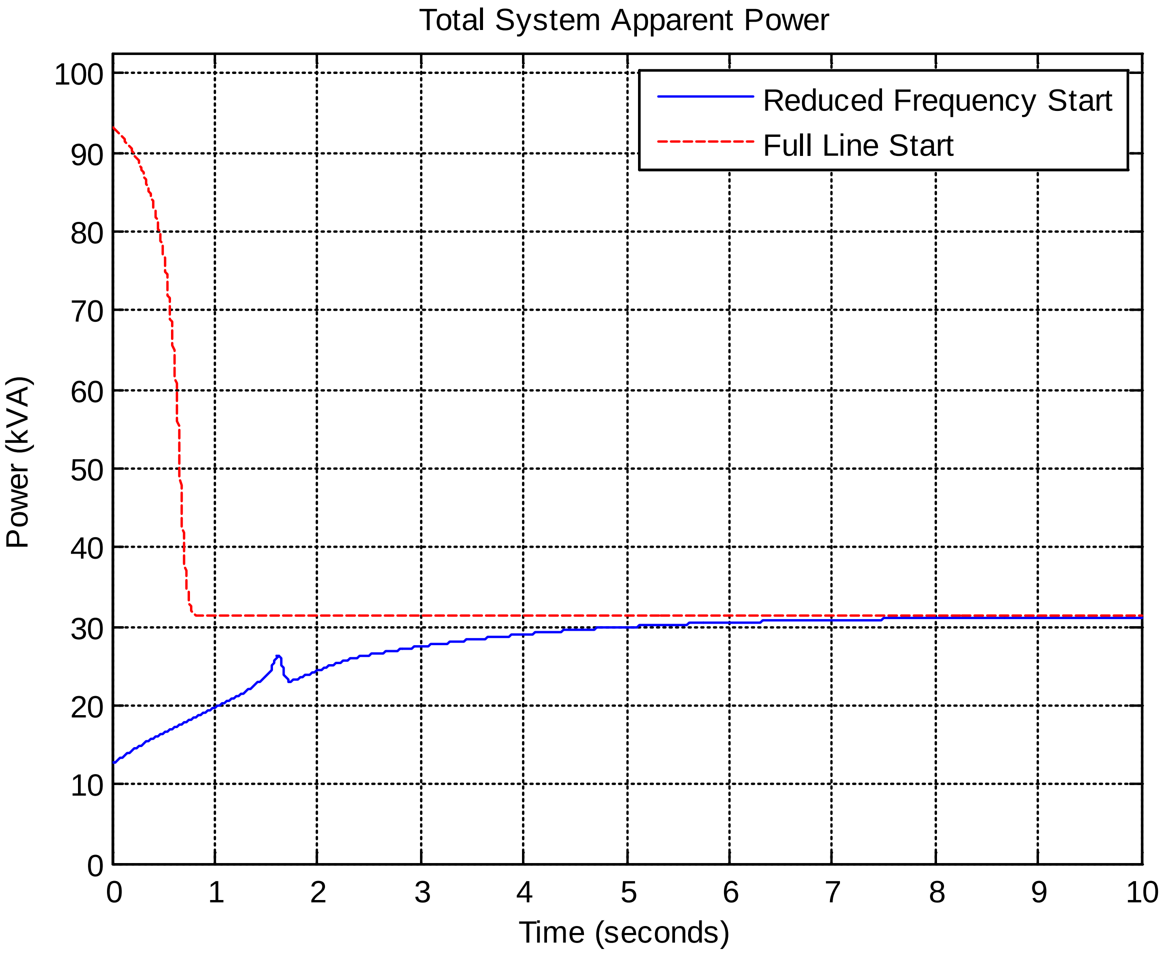


Figure 28: Case II – Total System Apparent Power

Case III: 20 hp pump only

The final case in this study involves a system that contains only the 20 hp pump. Figures 29-33 show the excitation and terminal voltages, motor current, motor speed, system average power input and system apparent power input, respectively, for Case III. The plot that tells the most important story is presented in Figure 33 which shows the total system apparent power demanded by the system. Again, there are significant savings when using the technique outlined in this paper. With a full line start, the maximum apparent power requirement of the system peaks at 81.60 kVA. When using the reduced frequency technique, the maximum apparent power requirement is 24.68 kVA. In this case, the required apparent power supplied is reduced 70%.

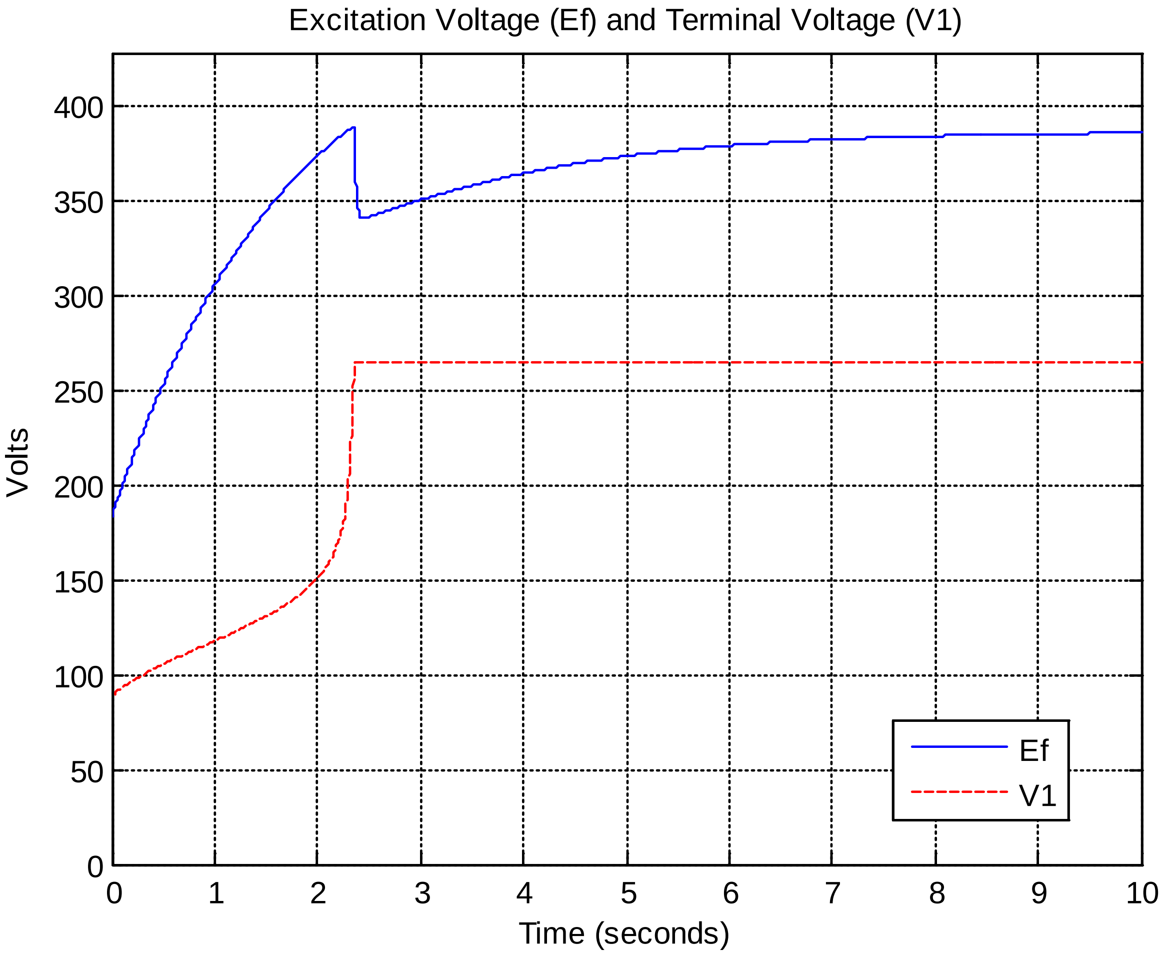


Figure 29: Case III – Excitation and Terminal Voltages

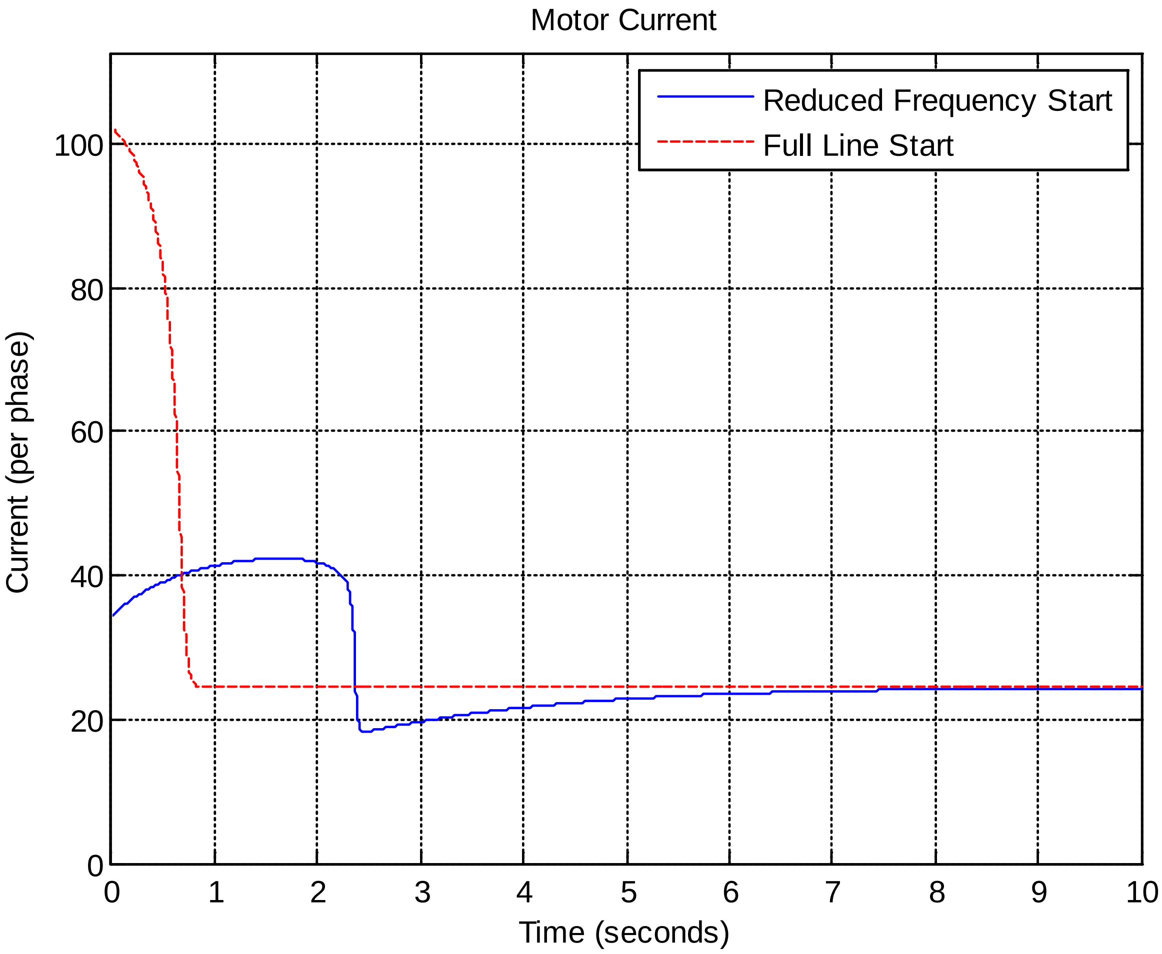


Figure 30: Case III – Current into the Motor

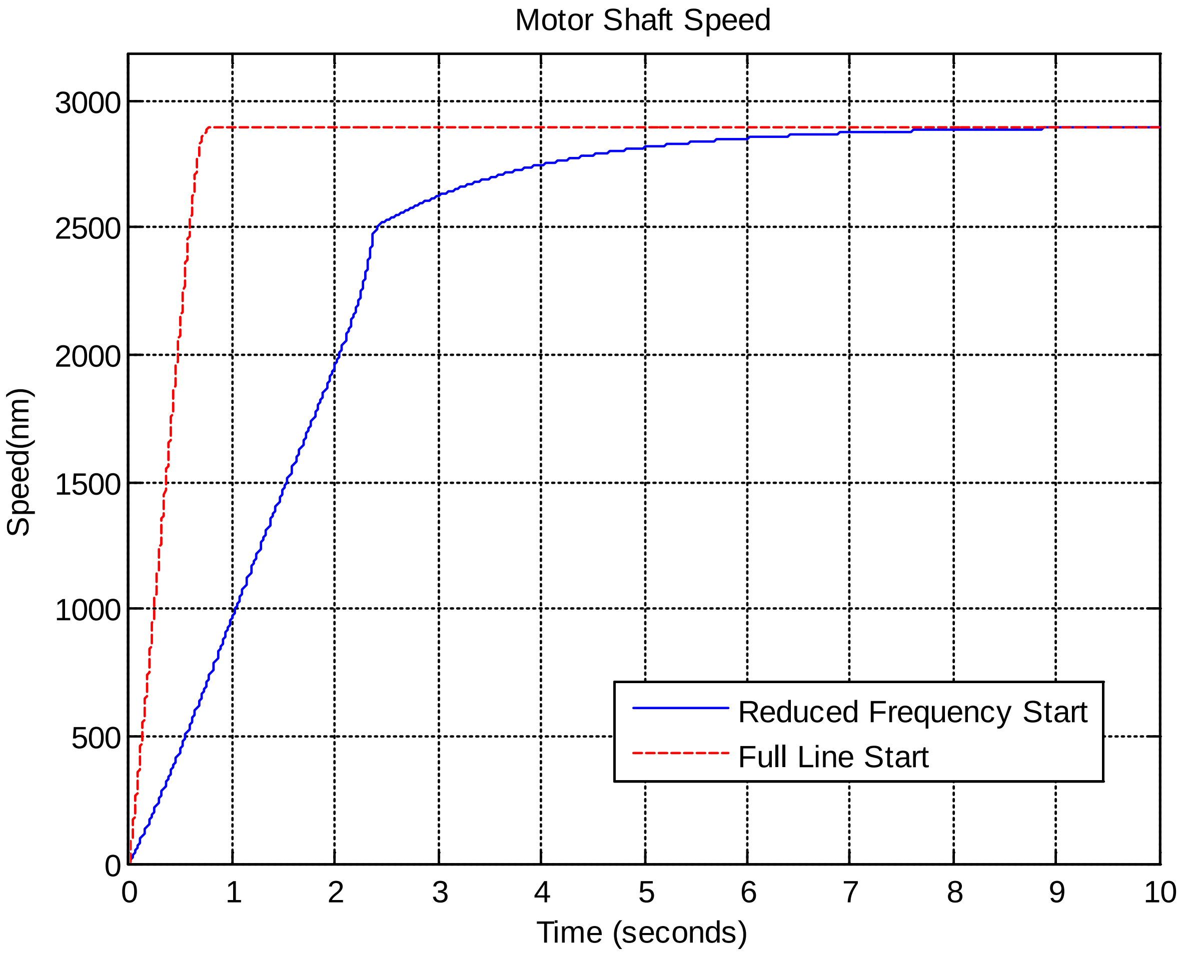


Figure 31: Case III – Motor Shaft Speed

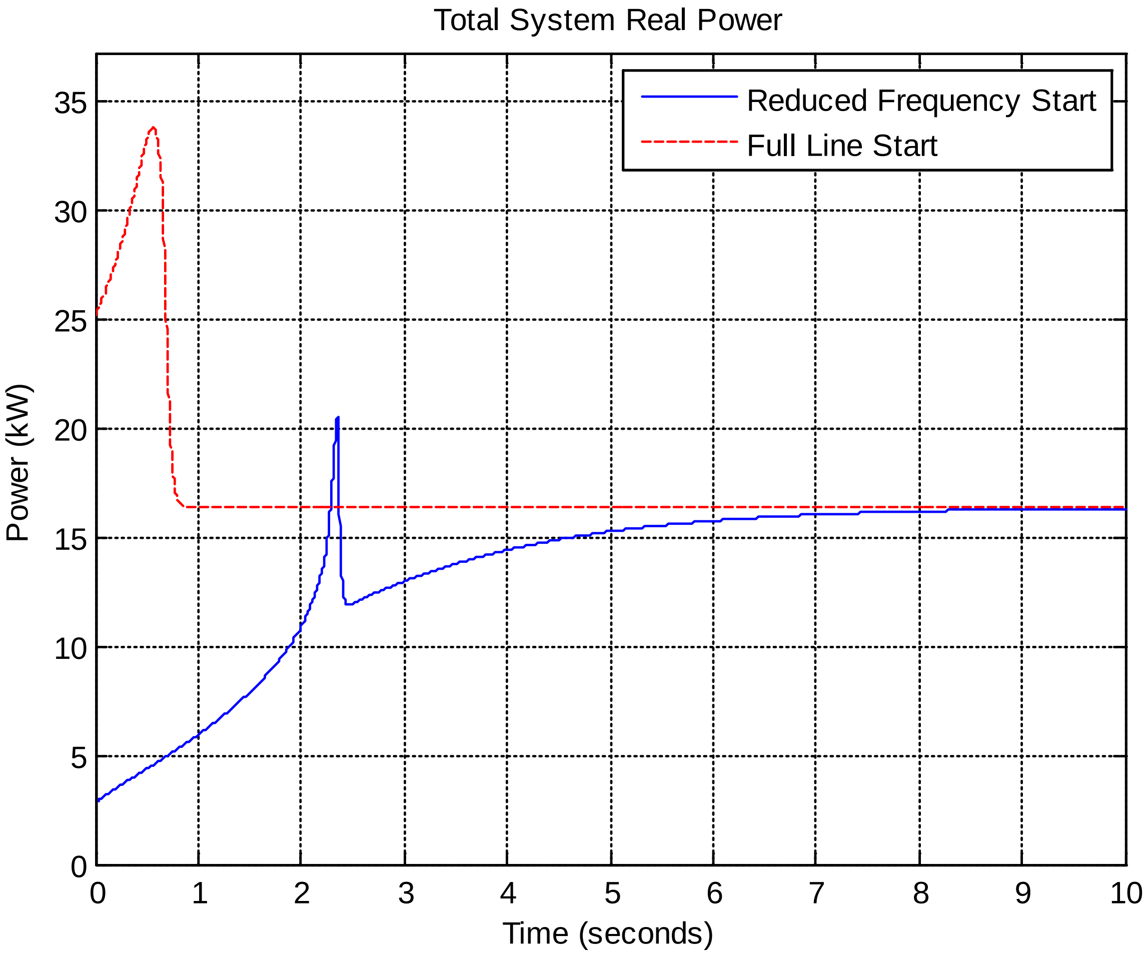


Figure 32: Case III – Total System Real Power

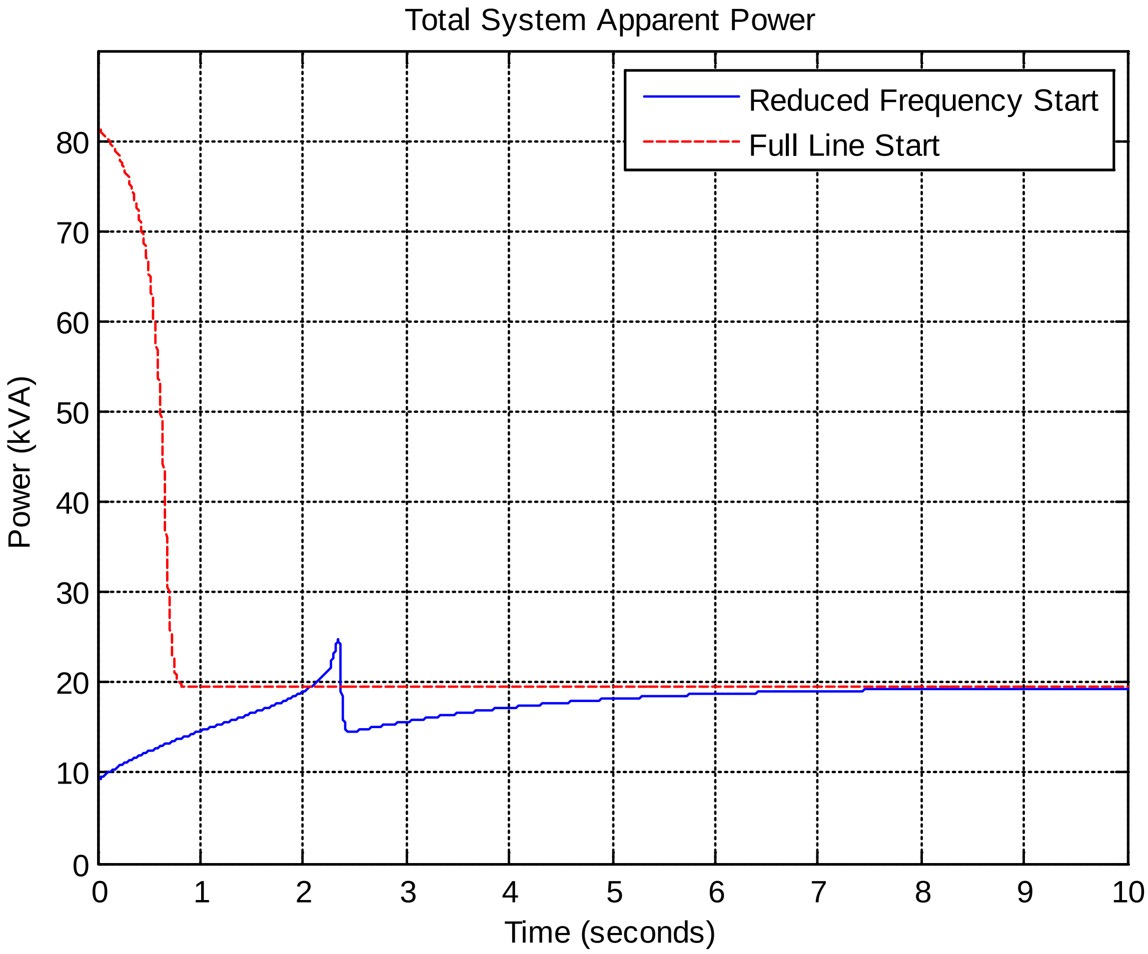


Figure 33: Case III – Total System Apparent Power

Critical Points

As shown in the previous figures, the key plot illustrating the effectiveness of the technique is the required power to operate the system. There is a critical region within which one can work in order to optimize the utilization of the system. In Figure 34, is an approximate plot of what the required power of a system using the technique would be if there was no initial spike in current due to the starting of the motor. The area that lies below the steady state power requirement (30.76 kVA in this case) during startup is a "free power region." There is no appreciable benefit to keeping the required power below the steady state power level, especially if in doing so causes more disturbances in the electrical service.

Using Case II with the 10 kW parallel load with a starting generator speed of 600 rpm (40% synchronous speed), it is evident that the initial spike of kVA required is the limiting factor as seen in Figure 24. It is also evident that at a starting speed of 600 rpm in both Cases I and II, that the peak of the inrush kVA spike exists below the level found when starting with full voltage and frequency. In particular, the peak of the kVA demand spike in Case I is less than the steady state power requirement of the system. When this occurs, it is an indication that the respective starting speed of 600 rpm is lower than what is necessary. This is significant in that, as mentioned in the statement of the problem, as the starting speed is further lowered, there is introduced more dimming/flickering of the lights and general variation of power flow. In order to

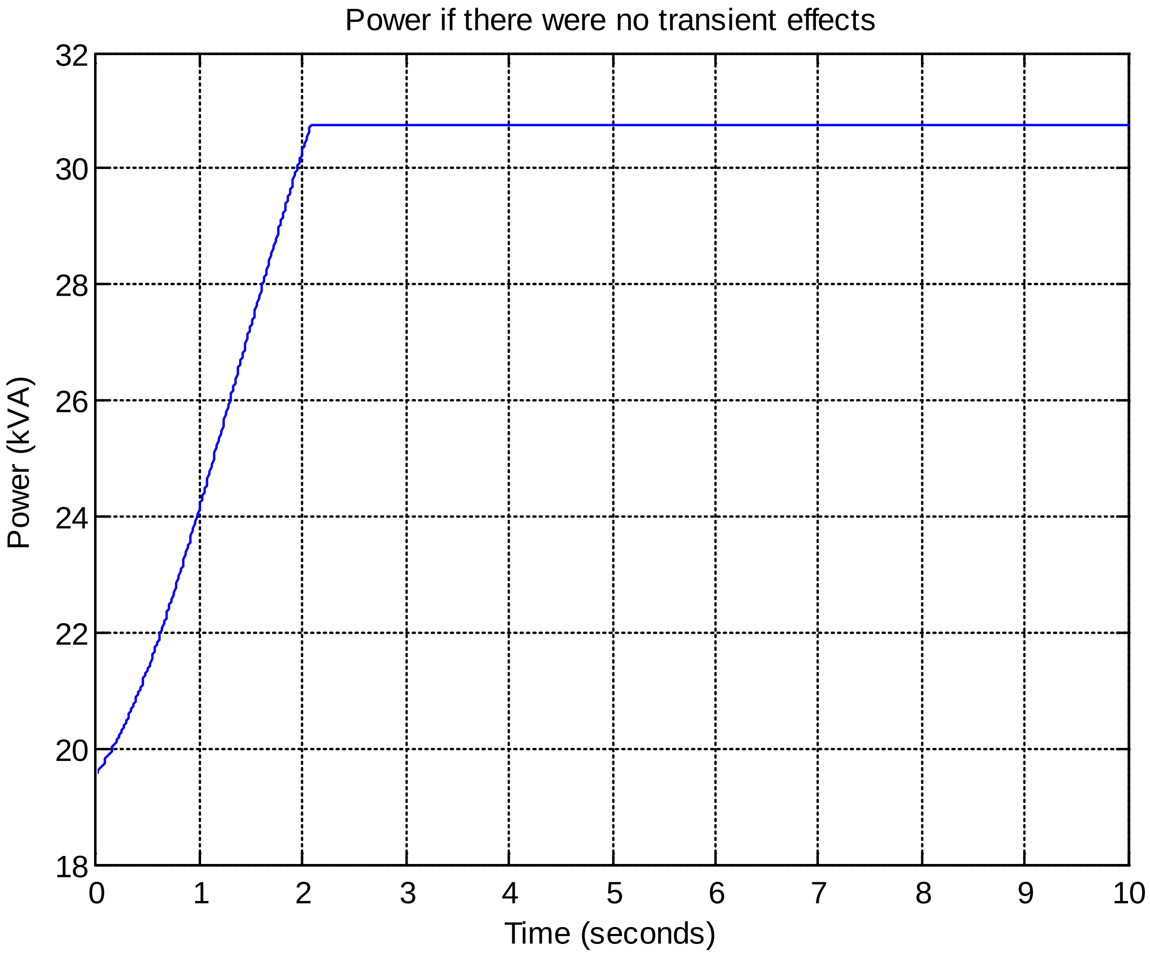


Figure 34: Total System Power if there was No Transient Effects in the Motor

optimize the use of the technique, one must discover a way to maximize the use of the "free power region." Again, I call this the "free power region" because the system is equipped to handle loads in this region at and below the steady state power requirement. Thus it is fruitless to try to attain savings below this point, especially if it is at the expense of the performance of anything else in the system.

As previously articulated, there is an optimal starting point that will yield favorable power flow dynamics while minimizing the reduction of the speed of the generator. This optimized starting point will be referred to as the "critical point." This critical point can be discovered by running the model using incremental values for the starting generator speed (the amount the rack is pulled back).

First, Case I is evaluated. Figure 35 shows the percent improvement (reduction in maximum required generator apparent power) in the system using the technique versus the percentage of synchronous speed that the generator engine is reduced to. Looking at the plot, it is evident that reducing the speed below the critical point of 70% of synchronous speed is pointless. Figure 36 shows the power consumption of the system when the critical point is utilized.

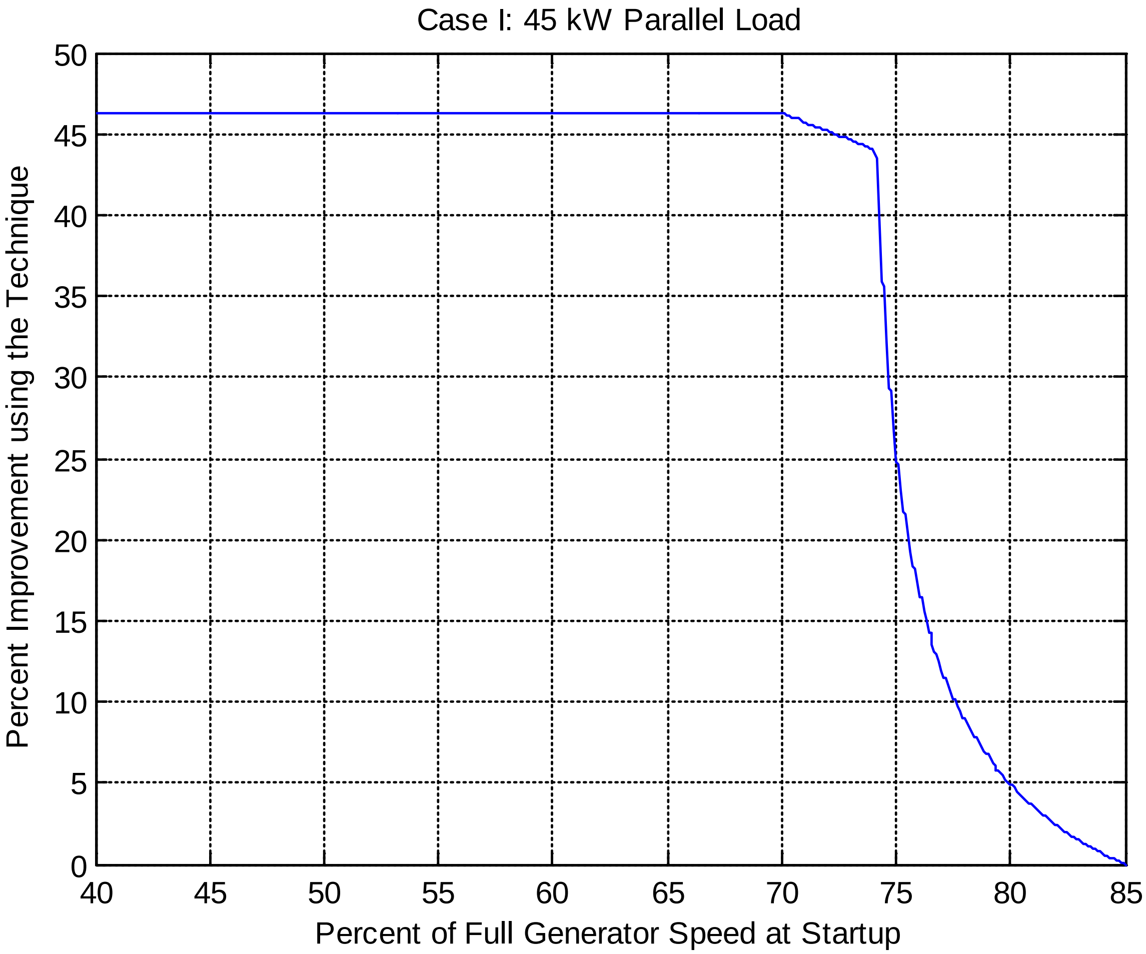


Figure 35: Case I - Percent Improvement

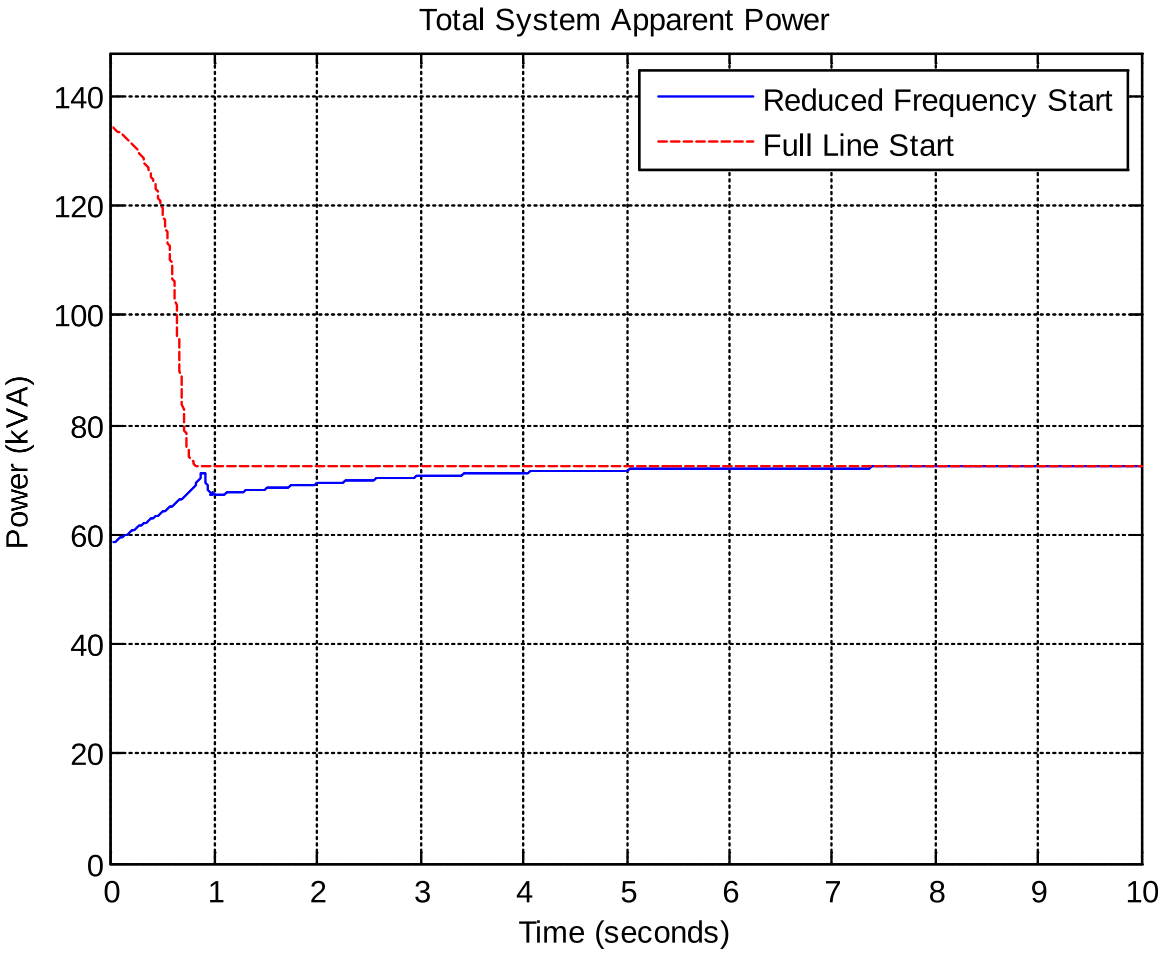


Figure 36: Case I – System Power with the Critical Point Utilized

It is evident that the critical point is where the peak of the kVA demand during inrush is equal to the steady state power requirement of the system.

Next, Case II is explored. Figure 37 shows the percent improvement in the system using the technique versus the percentage of synchronous speed to which the generator engine is reduced. Looking at the plot, it is evident that reducing the speed below the critical point of 49% of synchronous speed is pointless. Figure 38 shows the power consumption of the system when the critical point is utilized.

Finally, Case III is explored. Looking at Figure 33, it appears that reducing the speed below 40% of synchronous speed may further improve the performance. However, because lowering the generator speed below 40% compromises the system ability to provide adequate torque to start the pump, thus is not considered an option and the minimum of 40% would be considered its critical point. Again, Figure 33 has already illustrated the power consumption of the system when the critical point is utilized.

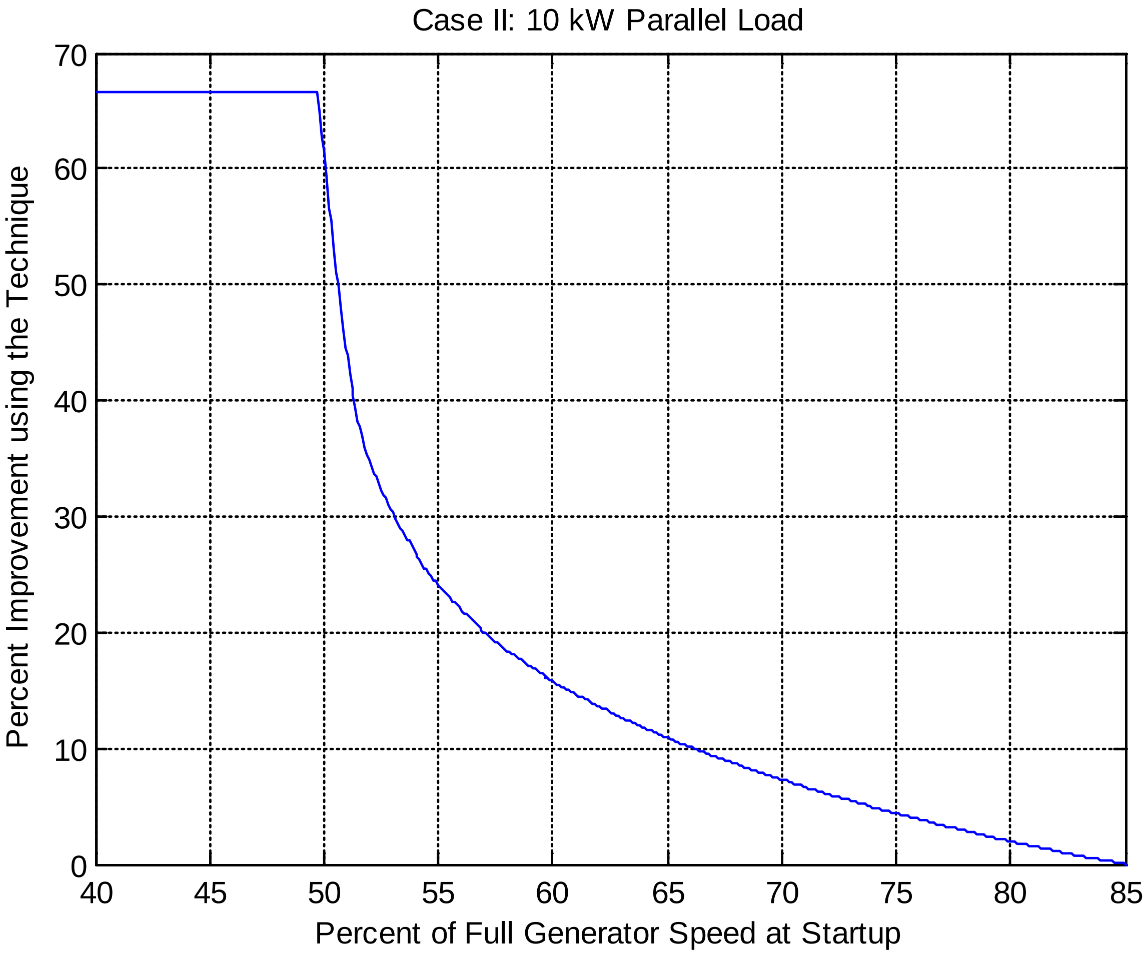


Figure 37: Case II - Percent Improvement

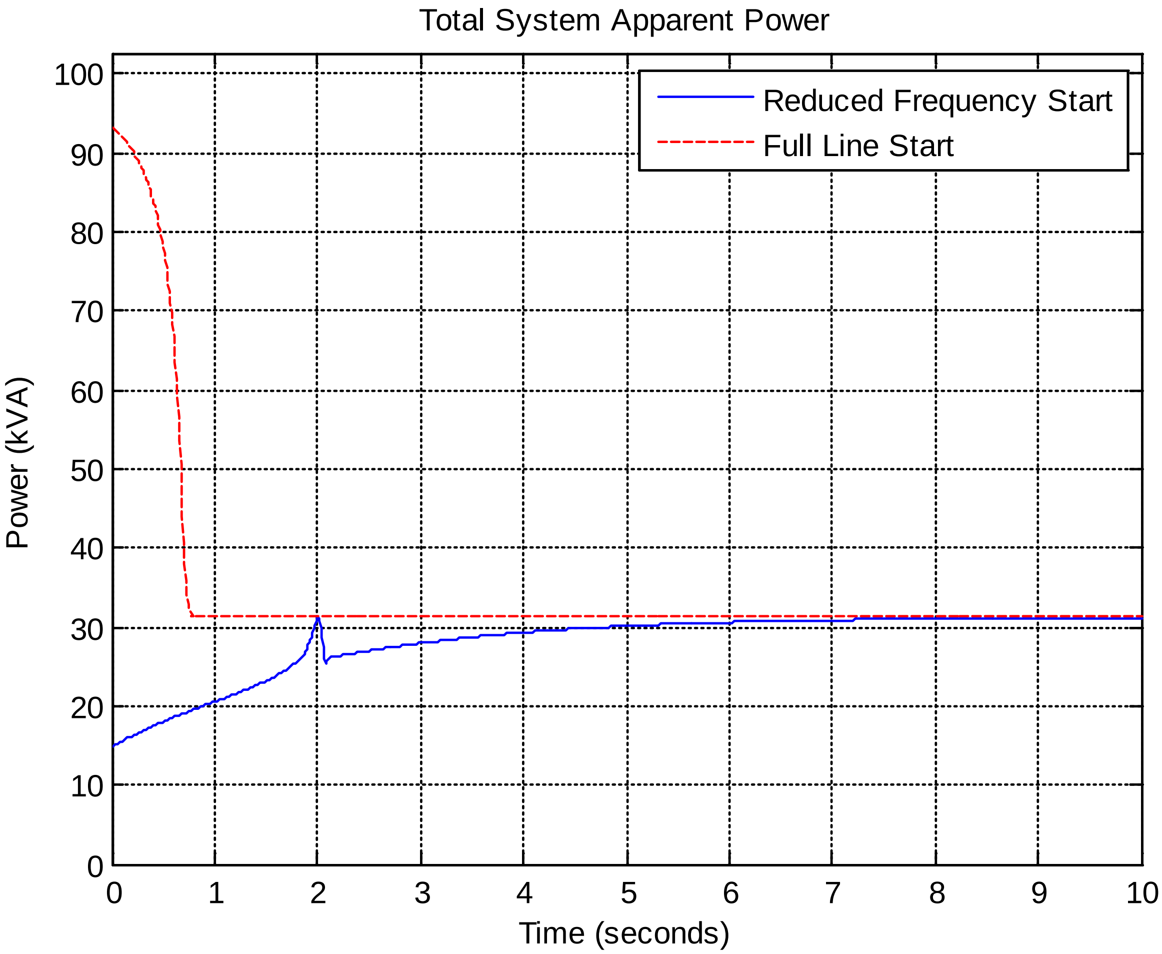


Figure 38: Case II – Total System Power with the Critical Point Utilized

Generator Excitation Type

As mentioned in Chapter 3, there is a choice to be made concerning which type of generator to choose for this situation. The choices mentioned were separately excited and self excited. By comparing system performance using the two different types of excitation, it becomes an easy decision to select the self excited generator. This improved performance occurs due to the shape of its respective voltage-frequency curve, including the fact that the self excited generator provides a higher initial terminal voltage. This makes the amount of change required, from the initial voltage to the final voltage, smaller while still being low enough to help offset the transient spike in current at a poor power factor. Its characteristically linear increase in excitation voltage (shown in Figure 18) manages the motor load in more consistent and steady manor as opposed to the parabolic increase (shown in figure 17) that occurs with a separately excited generator. Figures 39-43 illustrate the difference in performance of the two types using system setup in Case II.

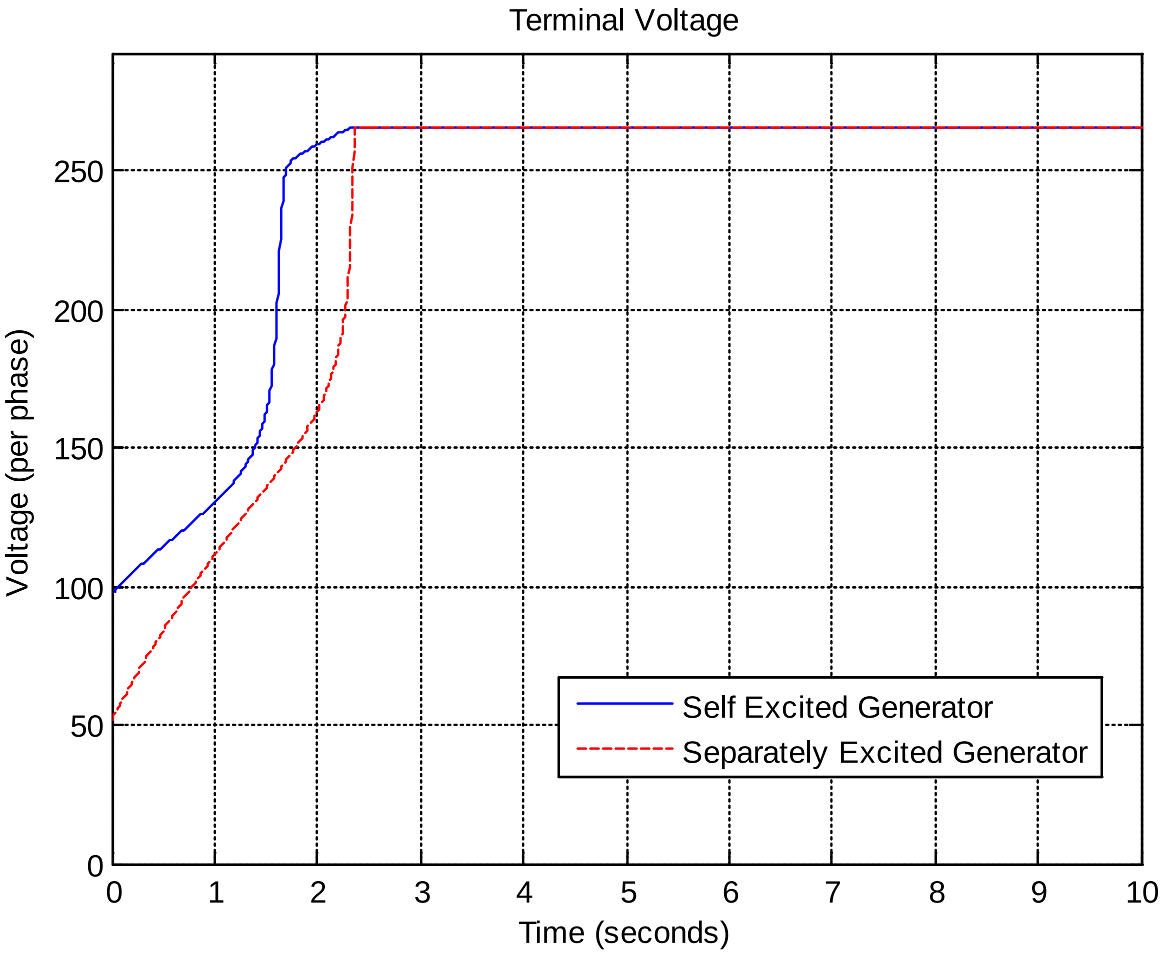


Figure 39: Self versus Separately Excited – Terminal Voltage

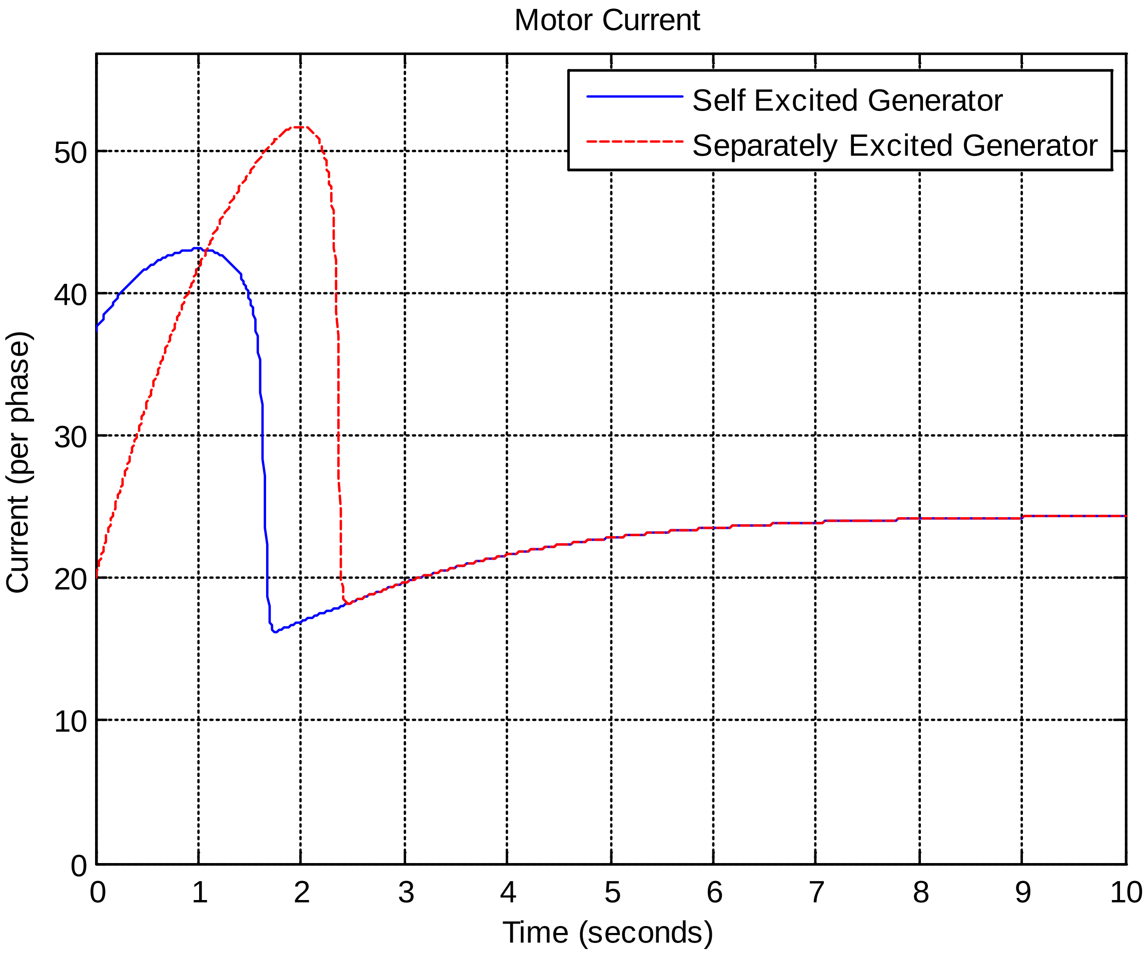


Figure 40: Self versus Separately Excited – Current into the Motor

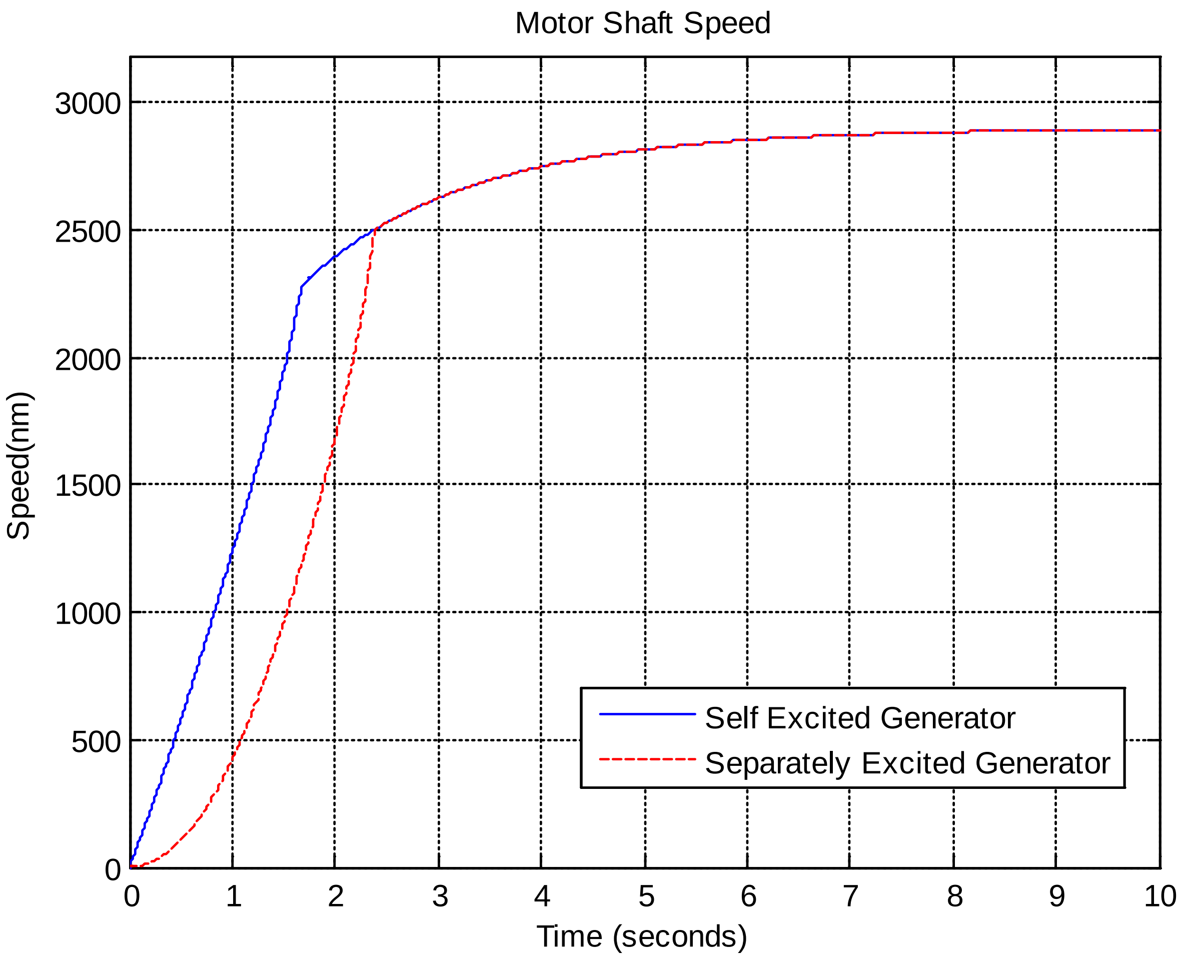


Figure 41: Self versus Separately Excited – Motor Shaft Speed

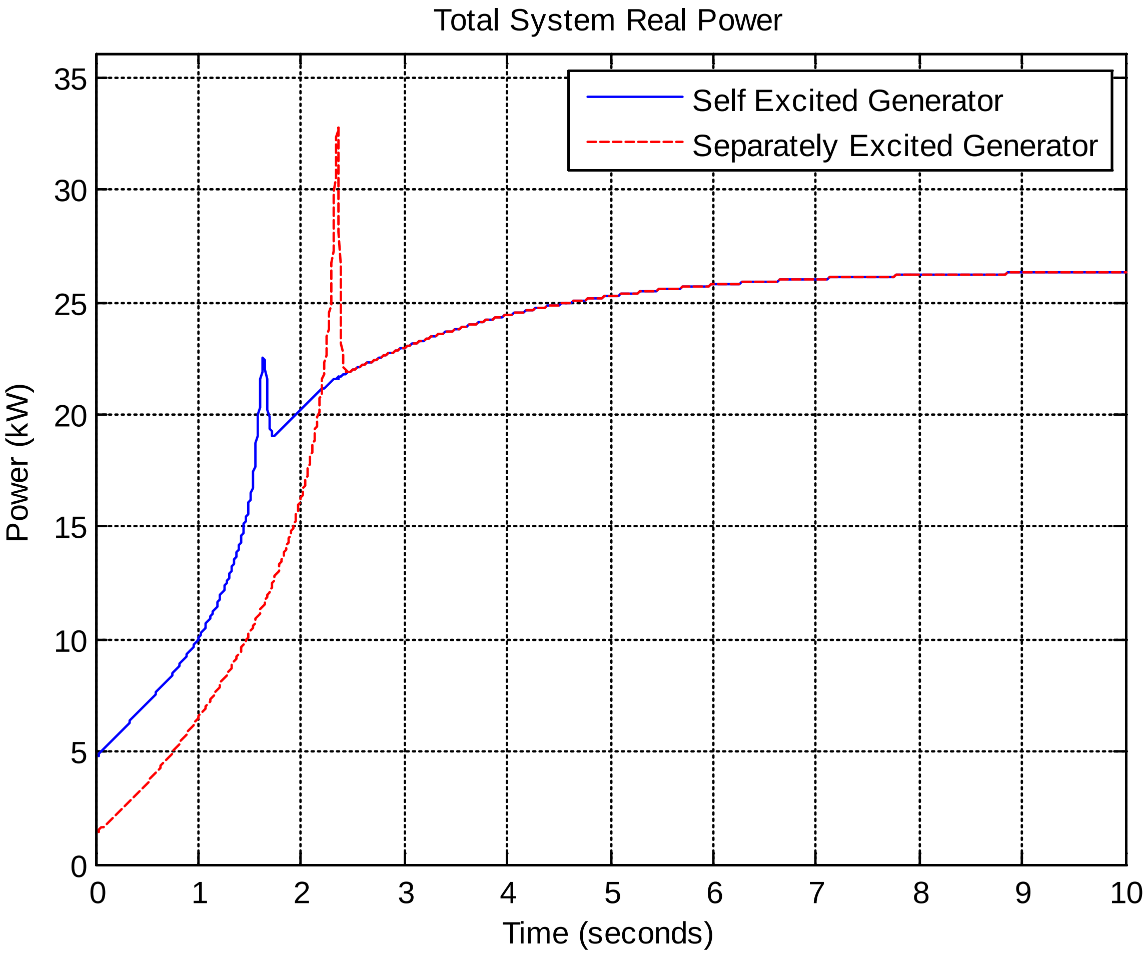


Figure 42: Self versus Separately Excited – Total System Real Power

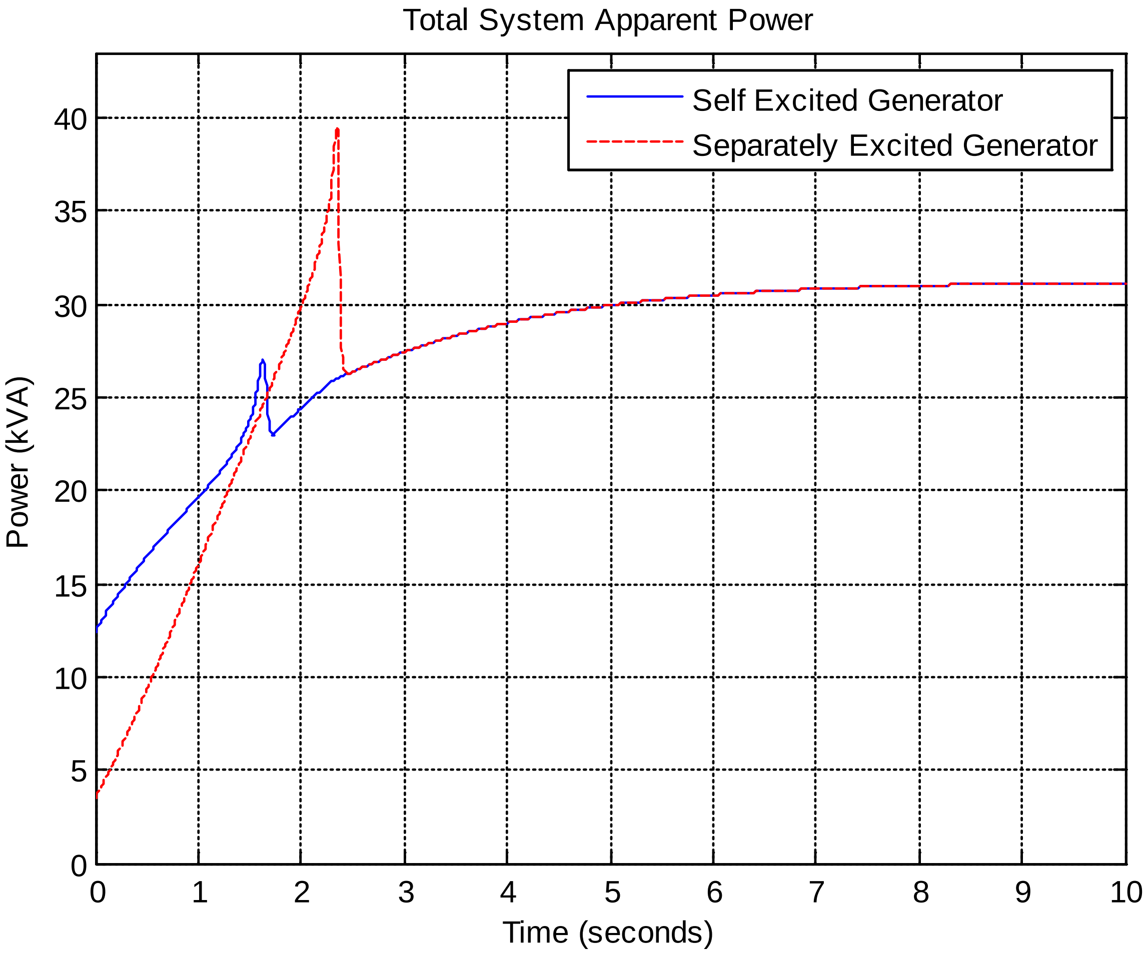


Figure 43: Self versus Separately Excited – Total System Apparent Power

Chapter 5: Conclusions

As evident from the plots of the results in the previous section, this is certainly an effective means of reducing the size of a generator to serve the load as laid out in the problem. Again, it is important to look back on two prominent affects of this solution.

The first would be the great financial benefit that comes with the reduction of the generator size. As mentioned in an example during the presentation of the problem. The savings using this technique can end up in the thousands of dollars. That amount of money saved very well could end up making a project move forward as opposed to canceled due to budget constraints. Further, in the event that there were available funds for purchasing an oversized generator, one could use the technique from this paper to save that money and put it toward other areas in the project.

Secondly, this is a very practical solution. While the quality of the power to the system is somewhat compromised for a couple of seconds, this is completely acceptable given the situation in which this is going to be used. As far as execution of the technique, the process of pulling back the rack and bringing on the motor load is very simple and most anyone could be trained to perform such a task.

Chapter 6: Recommendation for Future Work

There are several avenues one could pursue in the future building upon what has been discussed in this paper. This is by no means an exhaustive list, but some suggestions of what the author would find interesting.

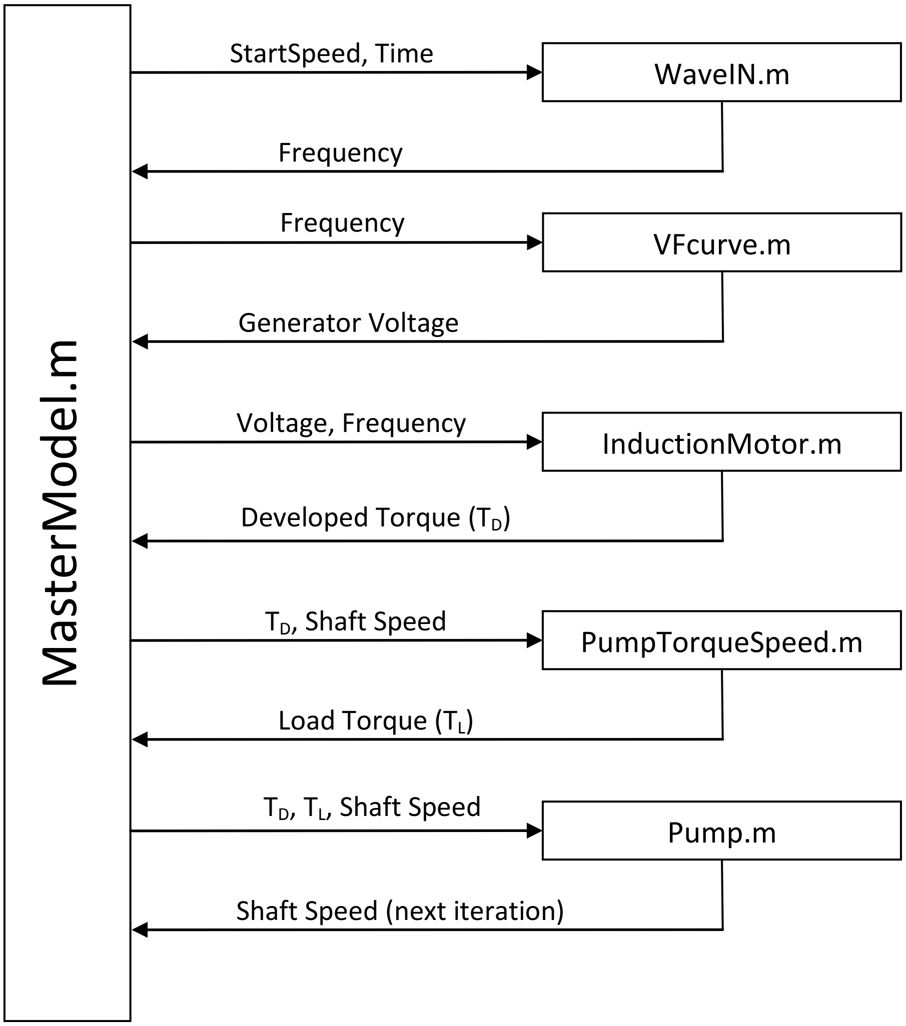
In this paper, the focus is on one pump load along with a given amount of common loads. While the purpose of the pump in this simulation is to provide much need water to the community, there are certainly other pumps or other loads that are driven by large motors. Future studies could investigate the effects of multiple motor loads at startup with various load characteristics that may differ from the load characteristic in the centrifugal pump in this paper.

Also, it would be interesting to apply this idea to alternate energy systems such as wind or solar power. Being able integrate this be even more beneficial than using a backup generator as discussed in this paper. Use of an alternate energy source would be more environmentally friendly and would make the community more self reliant, rather than being at the mercy of the unpredictable utility company. As mentioned in the presentation of the problem, one of the motivations of the technique in this paper is to reduce the cost and allow projects to be undertaken. While the cost of diesel generators are not trivial, the cost savings involved in buying less equipment for alternate energy sources such as solar panels, battery banks, etc. would be huge as the costs of said equipment dwarfs the cost of a diesel generator. Using this technique in that situation would involve reducing the inverter frequency in the same manner as the generator frequency was reduced in this paper. In certain cases, doing so could decrease the size of the battery bank needed to provide the startup currents required by the motor.

Appendices

Appendix A: MATLAB Code

The figure is a flow chart outlining the processes running during the simulation of the model. MasterModel.m is the master module that calls the various subroutines that all have their specific purposes.



MasterModel.m

```
% Taylor Begley
% MasterModel.m is the driver of the entire simulation
% This file will call the subroutines that will make the
% calculations to determine the outcome from the given conditions

clear all;close all;
disp('Begin Run')
global TSTART TSTOP TIME FFULL V1FULL PPL Ef1FULL; %global vars denoted by ALL CAPS

PPL = 45*1000; %desired parallel load in watts
TSTART = 0;     %start time for the simulation
TSTOP = 10;      %run simulation until time TSTOP (seconds)
numpoints = 1000;%number of testpoints
TIME = linspace(TSTART,TSTOP,numpoints);
FFULL = 50;     %frequency when running full
gpoles = 4;      %number of poles on generator
ns = 120*FFULL/gpoles;      %synchronous speed (rpm)

V1FULL = 460/sqrt(3); %per phase generator voltage (when at full voltage)
test=0;
global VERSUS STARTSPEED
% for STARTSPEED = 1:31
STARTSPEED=00;

Ef1FULL=514.2;
%Separately Excited    %514.2for 75/45;435 for 45/10;
%Self Excited     %434.35 for 35/10;514.2 for 75/45;
%389.58 for 30/0.0000000001
Gen=75000% kVA generator
Ilb=Gen/(460*sqrt(3));
Zb=(V1FULL)/Ilb;
Xs=1.0*Zb;
Ls=Xs/(2*pi*50);


for VERSUS=1:2
% Gen=35000% kVA generator
% Ilb=Gen/(460*sqrt(3))
% Zb=(V1FULL)/Ilb
% Xs=1.0*Zb
```

```
% Ls=Xs/(2*pi*50)
for k = 1 : numpoints
   ne(k) = WaveIN(TIME(k),ns);
   fe(k) = ne(k)*gpoles/120;%fe(k)=42.5;
   V1t(k) = VFcurveEf(fe(k));
   if k==1
      nm(1)=0;wm(1)=0;
       Zboth(k)=V1finder(fe(k),nm(k));%finds Zboth
   else
      nm(k)=(60/(2*pi))*wm(k);
       Zboth(k)=V1finder(fe(k),nm(k));%finds Zboth
   end
   Ztotal(k)=j*2*pi*fe(k)*Ls + Zboth(k);%j*wm(k)*Ls + Zboth(k);
   Itotal(k)=V1t(k)/Ztotal(k);
   Vs(k)=Itotal(k)*j*2*pi*fe(k)*Ls;%Itotal(k)*j*wm(k)*Ls;
   V1(k)=abs(V1t(k)-Vs(k));
   if VERSUS==2
      V1(k)=VFcurve(fe(k));
   end
   if fe(k) >= .85*50
     V1(k)=VFcurve(fe(k));
     V1t(k)=abs(V1(k)/Zboth(k)*j*2*pi*fe(k)*Ls + V1(k));
   end
   if k==1
      nm(1)=0;wm(1)=0;
      TTdandI1 = InductionMotor(V1(k),fe(k),nm(k));
   else
      nm(k)=(60/(2*pi))*wm(k);
      TTdandI1 = InductionMotor(V1(k),fe(k),nm(k-1));
   end

   TTd(k) = TTdandI1(1);I1(k) = TTdandI1(2);TPin(k) = TTdandI1(3);
      IReIm(k) = TTdandI1(4);kVAin(k) = TTdandI1(5);
   TL(k) = PumpTorqueSpeed(nm(k),TTd(k));
   if k < numpoints
      wm(k+1) = Pump(TTd(k),TL(k),wm(k),[TIME(k) TIME(k+1)]);
   end
   PP=ParallelLoad(V1(k),fe(k));
   Ipl(k)=PP(1);PPow(k)=PP(2);
%     k
%     pause;
Iph(k)=IReIm(k)+Ipl(k)/3;
   if fe(k) > 42.5
```

```
      if test ==0
        jwLs(k)=j*.85*50*2*pi*Ls;
        VjwLs(k)=(Iph(k)).*jwLs(k);
        V85=VjwLs(k);
        test = 1
      else VjwLs(k) =V85;
      end
   else
      jwLs(k)=j*fe(k)*2*pi*Ls;
      VjwLs(k)=(Iph(k)).*jwLs(k);
   end
tests(k)=test;
Ef(k)=V1(k)+VjwLs(k);
end

Itot=I1+real(Ipl);
Isys=IReIm+Ipl;
PFsys=cos(angle(Isys));

if VERSUS == 1
   c='b-';
else c='r--';end
rfs='Reduced Frequency Start';
fls='Full Line Start';
figure(1) %plot Generator speed output
plot(TIME,ne,c)
axis([TSTART TSTOP 0 ns*1.1]);title('Generator speed');
xlabel('Time (seconds)');ylabel('Speed (rpm)');grid on;
hold on;legend(rfs,fls)

if VERSUS ==1
figure(2) %plot characteristic Voltage-Frequency Curve
% ftest = linspace(min(fe),FFULL,50);
% for char = 1:length(ftest)
%     VFchar(char) = VFcurveEf(ftest(char));
% end
% plot(ftest,VFchar,c); title('Separately Excited Generator Characteristic Curve');
plot(fe,V1t,c); title('Self Excited Generator Characteristic Curve');
xlabel('Frequency (Hz)');ylabel('Excitation Voltage (per phase)');grid on;axis([20 42.5 200
550]);
end
% hold on;legend(rfs,fls)
```

```
figure(3) %plot voltage regulated V1
V1x(VERSUS)=max(abs(V1));
plot(TIME,abs(V1),c)
axis([TSTART TSTOP 0 max(V1x)*1.1]);title('Voltage V1');
xlabel('Time (seconds)');ylabel('Voltage (per phase)');grid on;
hold on;legend(rfs,fls)

figure(4) %plot motor current
plot(TIME,abs(I1),c)
axis([TSTART TSTOP 0 max(abs(I1))*1.1]);title('Motor Current');
xlabel('Time (seconds)');ylabel('Current (per phase)');grid on;
hold on;legend(rfs,fls)

figure(5) %plot developed Torque
plot(TIME,TTd,c)
axis([TSTART TSTOP 0 max(TTd)*1.1]);title('Developed Torque');
xlabel('Time (seconds)');ylabel('Torque');grid on;
hold on;legend(rfs,fls)

figure(6) %plot load Torque
plot(TIME,TL,c)
axis([TSTART TSTOP 0 max(TL)*1.1]);title('Load Torque');
xlabel('Time (seconds)');ylabel('Torque');grid on;
hold on;legend(rfs,fls)

figure(7) %plot accelerating Torque
plot(TIME,TTd-TL,c)
axis([TSTART TSTOP 0 max(TTd-TL)*1.1]);title('Accelerating Torque');
xlabel('Time (seconds)');ylabel('Torque');grid on;
hold on;legend(rfs,fls)

figure(8) %plot nm
plot(TIME,nm,c)
axis([TSTART TSTOP 0 max(nm)*1.1]);title('Motor Shaft Speed');
xlabel('Time (seconds)');ylabel('Speed(nm)');grid on;
hold on;legend(rfs,fls)

figure(9) %plot Power into motor
TPin=TPin;
plot(TIME,TPin/1000,c)
axis([TSTART TSTOP 0 max(TPin/1000)*1.1]);title('Real Power into Motor');
xlabel('Time (seconds)');ylabel('Power(kW)');grid on;
hold on;legend(rfs,fls)
```

```
TPin(numpoints)

figure(10) %plot Power into motor
plot(TIME,kVAin/1000,c)
axis([TSTART TSTOP 0 max(kVAin/1000)*1.1]);title('Apparent Power into Motor');
xlabel('Time (seconds)');ylabel('Power(kVA)');grid on;
hold on;legend(rfs,fls)
TPin(numpoints)

figure(11) %plot Power Tw
PowerTw=TTd.*wm;
plot(TIME,PowerTw/1000,c)
axis([TSTART TSTOP 0 max(PowerTw/1000)*1.1]);title('Power TTd*wm to Pump');
xlabel('Time (seconds)');ylabel('Power(kW)');grid on;
hold on;legend(rfs,fls)
PowerTw(numpoints)

% figure(12) %plot motor efficiency
% eff=PowerTw./TPin*100;
% plot(TIME,eff,c)
% axis([TSTART TSTOP 0 max(eff)*1.1]);title('Motor Efficiency PowerTw/PowerVI');
% xlabel('Time (seconds)');ylabel('Efficiency %');grid on;
% hold on;legend(rfs,fls)

SteadyStateShaftSpeed=wm(numpoints)*30/pi
% figure(13) %plot Power current *
% PPo=PPo./1000;%voltage power in kVA
% plot(TIME,PPo,c)
% axis([TSTART TSTOP 0 max(PPo)*1.1]);title('PPo');
% xlabel('Time (seconds)');ylabel('Power(kW)');grid on;
% hold on;legend(rfs,fls)
% max(PPo)

% figure(14) %Parallel load current
% plot(TIME,real(Ipl),c)
% axis([TSTART TSTOP 0 max(Ipl)*1.1]);title('Parallel Load Current');
% xlabel('Time (seconds)');ylabel('Current');grid on;
% hold on;legend(rfs,fls)

figure(15) %Parallel load Power
Powerpl=real(Ipl.*V1);
Powerpl=real(PPow);
Powerpl=abs(V1).*abs(Ipl).*cos(angle(V1)-angle(Ipl));
```

```
PPx(VERSUS)=max(abs(Powerpl));
plot(TIME,(Powerpl/1000),c)
axis([TSTART TSTOP 0 max(PPx/1000)*1.1]);title('Parallel Load Real Power');
xlabel('Time (seconds)');ylabel('Power (kW)');grid on;
hold on;legend(rfs,fls)

figure(16) %Total System Power
PowerSYS=Powerpl+TPin;
plot(TIME,PowerSYS/1000,c)
axis([TSTART TSTOP 0 max(PowerSYS/1000)*1.1]);title('Total System Real Power');
xlabel('Time (seconds)');ylabel('Power (kW)');grid on;
hold on;legend(rfs,fls)

figure(17) %Total System kVA
kVASYS=abs(Powerpl/0.85+kVAin);
plot(TIME,kVASYS/1000,c)
axis([TSTART TSTOP 0 max(kVASYS/1000)*1.1]);title('Total System Apparent Power');
xlabel('Time (seconds)');ylabel('Power (kVA)');grid on;
hold on;legend(rfs,fls)

% figure(18) %Total System Power Factor
% plot(TIME,PFsys,c)
% axis([TSTART TSTOP 0 1]);title('Total System Power Factor');
% xlabel('Time (seconds)');ylabel('Power Factor');grid on;
% hold on;legend(rfs,fls)
figure(18) %Parallel load Power
plot(TIME,((Powerpl/.85)/1000),c)
axis([TSTART TSTOP 0 max((PPx/.85)/1000)*1.1]);title('Parallel Load Apparent Power');
xlabel('Time (seconds)');ylabel('Power (kVA)');grid on;
hold on;legend(rfs,fls)
% figure(19) %Power Ratio of Motor Power/Total Power
% PowerRatio=TPin./PowerSYS;
% plot(TIME,PowerRatio*100,c)
% axis([TSTART TSTOP 0 100]);title('Motor Power/System Power');
% xlabel('Time (seconds)');ylabel('Ratio (%)');grid on;
% hold on;legend(rfs,fls)

figure(20)%plot Ef versus V1
if VERSUS ==1
   plot(TIME,V1t,'b');hold on
   plot(TIME,abs(V1),'r--');
   axis([TSTART TSTOP 0 max(V1t)*1.1]);title('Excitation Voltage (Ef) and Terminal
Voltage (V1)');
```

```
   xlabel('Time (seconds)');ylabel('Volts');grid on;
   legend('Ef','V1')
end


PC(VERSUS)=max(kVASYS);
end%VERSUS

MAXkVA_With_Without_Ratio_PPL=[PC(1)/1000 PC(2)/1000 PC(1)/PC(2)
(V1FULL*real(Ipl(numpoints)))/1000]
```

WaveIN.m

```
%  This m-file is going to give a wafeform into the system
%  based on the pulling back of the rack on the diesel generator
%  Given a time (t), it will output ne (electrical speed)

function [ne] = WaveIN(t,ns)
global VERSUS STARTSPEED

 initspeed = (STARTSPEED+40)/100*ns;%Initial speed at Time Zero

if VERSUS == 1
   ne = ns -(ns-initspeed)*exp(-t/1.5);
else ne=ns;
end
```

VFcurve.m

```
% This m-file is called by MasterModel.m and is the representative
% voltage-frequency curve that portrays voltage regulation
% input frequency, output is the voltage

function [V1] = VFcurve(f)

global V1FULL FFULL;

fmin = .85 * FFULL;
if f >= fmin
   V1 = V1FULL;
else
%    V1 = (V1FULL / fmin) * f;%self excited
   V1 = V1FULL/fmin^2 * f^2;%separately excited
```

```
end
```

InductionMotor.m

```
%  InductionMotor.m - calculates induction motor performance ( I1, PF,
% 3Td, Ps, efficiency ) based on equivalent circuit
% Reads equivalent circuit parameters from im_data.m

function [TTdandI1] = InductionMotor(V1,f,nm)

IM_DATA,
global V1FULL FFULL;% p=4;  % Phase voltage, frequency, poles

poles=2;

ns = 120*f/poles;      %synchronous speed (rpm) based on current freq
ws=2/poles*2*pi*f;
s = (ns-nm)/ns; % Slip

Pfw=700;
Tfw= (Pfw*(30/pi)/2900)*(1-s);

% Empirical adjustment of R2pr & X2pr for fr variation
R2pr0=R2pr; X2pr0=X2pr; smax=R2pr/sqrt(R1^2+(X1+X2pr)^2);

  if s > smax
  R2pr=(0.5+0.5*sqrt(s/smax))*R2pr0;
  X2pr=(0.4+0.6*sqrt(smax/s))*X2pr0;
  else; R2pr=R2pr0; X2pr=X2pr0; end

Z2 = R2pr/s+j*X2pr; Zm=j*Rc*Xm/(Rc+j*Xm);
Zin = R1+j*X1 + Z2*Zm/(Z2+Zm);
I11 = V1/Zin;
I1 = abs(I11);
PF = cos(angle(I11));
I2pr = abs(Zm/(R2pr/s+j*X2pr+Zm)*I11);
TPin = 3*V1*I1*PF;
TTd = 3*I2pr^2*R2pr/s/ws; nm=(1-s)*ns;
TTout = TTd - (Tfw);
kVAin=TPin/PF;

 PPo=TTd*(1-s)*ws - Pfw*(nm/ns)^n;
TTdandI1=[TTout I1 TPin I11 kVAin];
```

IM_DATA.m

```
% IM_DATA.m - contains induction motor equivalent circuit
%           parameter values to be read by calling program.

m=1.17;
R1=0.1*m; R2pr=.32*m;
X1=1.30*m; X2pr=1.35*m;
Rc=330*m; Xm=27.59512*m;
```

PumpTorqueSpeed.m

```
% PumpTorqueSpeed.m inputs the current speed and developed torque
% uses a characteristic Torque-Speed curve of centrifugal pump
% to output the load torque after making sure that the load torque
% does not exceed the developed torque

function [TL] = PumpTorqueSpeed(nm,Td)

wm = nm * (pi/30);

%below is the calculated parabola to fit
%the pumps speed torque characteristic
TL = 0.000006866825208085613*(wm.*30/pi)^2-
0.007603448275862068*(wm*30/pi)+6.3;

%check to ensure load torque does not exceed developed torque
if TL > Td
   disp('******Load torque(TL) exceeds developed torque(Td)******')
end
```

Pump.m

```
% Pump.m

function [wm_next] = Pump(Td,TL,wm,tspan)

J = .1547; %Define the pumps inertia
FW=6; %beta*wm for the rated speed
beta = FW/(3000*pi/30);
```

```
% define the diff equ in the form w' = C1 + C2*w
global C1 C2;
C1 = (Td-TL)/J;
C2 = -beta/J;

[t,wm_n] = ode23('PumpODE',tspan,wm);

wm_next=wm_n(length(wm_n));
```

PumpODE.m

```
% PumpODE.m

function wmprime = PumpODE(t,wm);
global C1 C2;
wmprime = C1 + C2*wm;
```

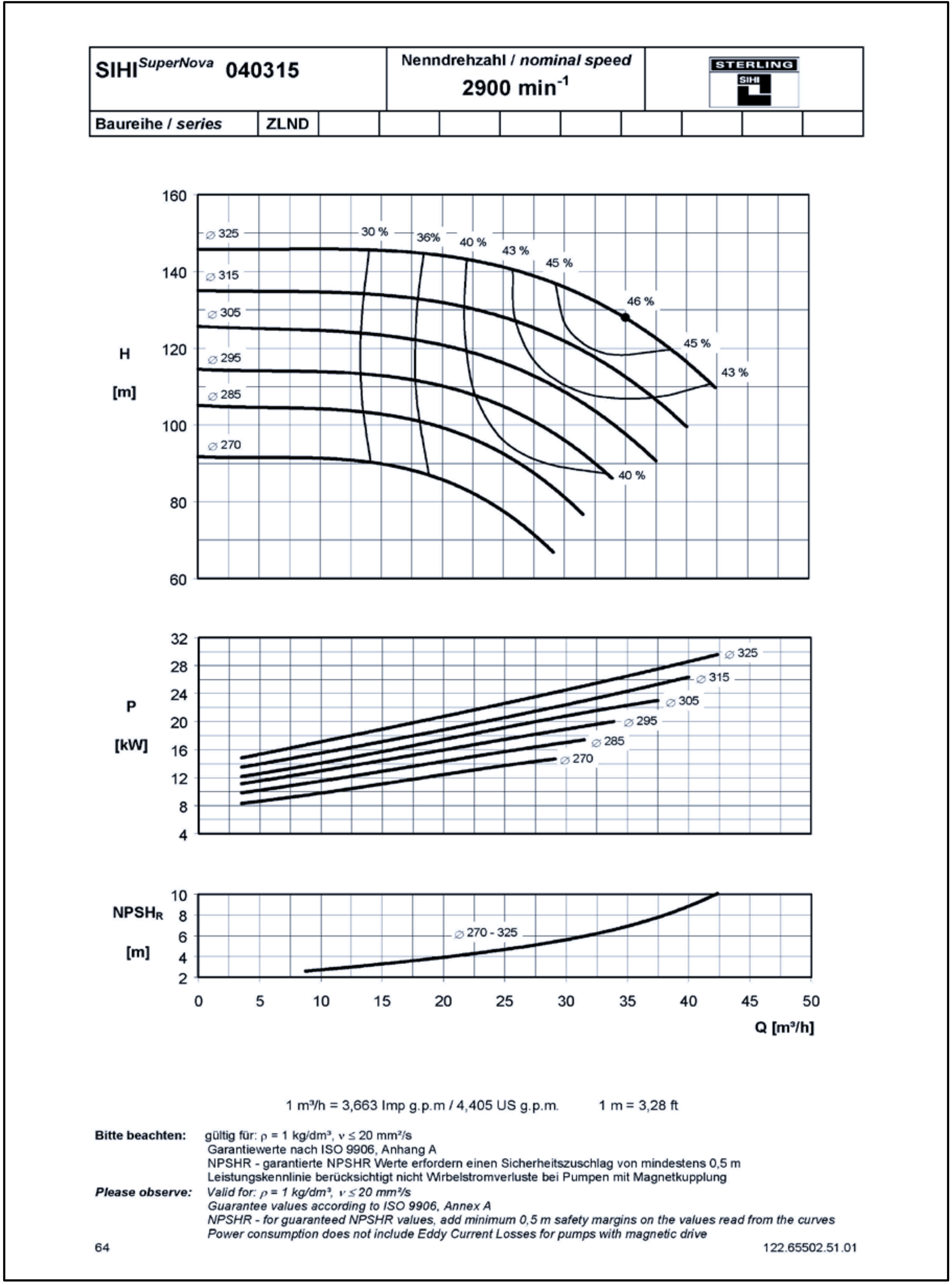
ParallelLoad.m

```
% ParallelLoad.m is the load that is
% in parallel with the motor/pump load
% this is to power lighting, rcpts, fans, etc.
% This will take the load on a per phase basis
% and out put the total requirement (phases balanced)

function [Ipl] = ParallelLoad(V1)
global V1FULL PPL

pf = 0.85;% Power Factor of the load
Ir=PPL/V1/3;
Pperphase=PPL/3;
R=.7225*(V1FULL^2)/Pperphase;
X=tan(acos(pf))*R;
I=V1/(R+j*X);
Ipl=3*I;
```

Appendix B: Centrifugal Pump Data



SIHI^{SuperNova} 040315	Nenndrehzahl / *nominal speed* 2900 min^{-1}	STERLING SIHI
Baureihe / *series*	ZLND	

1 m^3/h = 3,663 Imp g.p.m / 4,405 US g.p.m.   1 m = 3,28 ft

Bitte beachten: gültig für: ρ = 1 kg/dm^3, $\nu \leq$ 20 mm^2/s
Garantiewerte nach ISO 9906, Anhang A
NPSHR - garantierte NPSHR Werte erfordern einen Sicherheitszuschlag von mindestens 0,5 m
Leistungskennlinie berücksichtigt nicht Wirbelstromverluste bei Pumpen mit Magnetkupplung

Please observe: *Valid for: ρ = 1 kg/dm^3, $\nu \leq$ 20 mm^2/s*
Guarantee values according to ISO 9906, Annex A
NPSHR - for guaranteed NPSHR values, add minimum 0,5 m safety margins on the values read from the curves
Power consumption does not include Eddy Current Losses for pumps with magnetic drive

64   122.65502.51.01

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