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An Onboard Electrical Network Platform – Modeling & Simulation

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Abstract—**The performance of a shipboard power station, which is a typical large-scale and complex system, relates directly to marine safety. To guarantee ideal performance, control system should be able to maintain the frequency and terminal voltage of electrical network stable in both steady states and transient processes. However, even for a well-tuned controller, in some special cases, its configuration wouldn't be appropriate. If there is a mechanism that is able to detect the variation of topology of electrical network and assist the controller to prepare for it, it could facilitate the working of marine electrical engineer. To realize this idea, a project named as "research on control methods for onboard electrical network", is now under research. This paper is the first part work of this project and focuses on building a framework for marine power system. Based upon this framework, further researches about topology supervision and controller mutation are carried on. The mathematic models for onboard power system, their realization in Matlab, and some issues that attentions need to be paid to during the simulations are elaborated in this article.**

I. INTRODUCTION

WITH the prompt developments of international shipping trade, demands for large merchant marine vehicles, such as Ultra Large Container Ships (ULCS) and Very Large Crude Oil Carriers (VLCC), are increasing rapidly. At the same time, in the military field, to guarantee the requirements of enhancing reliability, All Electric Ships (AES) [1], which could also strengthen combat effectiveness of battlewagons, are the development direction. All these modern marine vessels, for both civilian and naval purposes, possessing a common feature of requiring larger electric power than traditional ones, utilize electric power not only for side thrusters, deck machineries, engine room auxiliaries, etc. but also for auxiliary or absolute electric propulsion. Therefore, "large capacity" power systems are necessary for these present-day ships. For example, the power plant of Queen Mary II, an ocean liner who can accommodate 2,620 passengers, could generate combined 117.2MW power with four diesel engines and two gas turbines [2].

As a consequence of the increasing capacity of marine power plant and single generator set, the complexity of power systems increase and higher requirements for power control and management are needed. Nevertheless, a marine power plant, compared with the "infinite" capacity of shore power system, has following characters and some of them make it difficult to be well controlled:

1) The capacity of onboard power system is relatively small. Although the biggest capacity of a single marine alternator could reach as big as several tens mega watt, this capacity perhaps is just enough for an asynchronous motor onboard, which will cause a big disturbance when it starts.

2) The marine machineries start and stop frequently, which would bring high frequency dynamic processes and make electrical network parameters, such as voltage and frequency, fluctuate often with high amplitude. This fluctuation would potentially damage electric devices.

3) The working conditions of marine electric equipments are awful. High temperature, humidity, salt mist, mildew and oil mist from environment are all guilty for conductive metal eroding; swaying motion and vibration from vessel are responsible for the damage of equipments' reliability and stability.

4) The power transmission distance onboard is short and the transmission voltage is low. Hereby, if short circuit faults happen, the damage to the alternator and also to the whole system will be huge.

The control and management of a marine power station come down to different aspects, such as maintain the stability for voltage and frequency, harmonic reduction, reactive power compensation, keeping three phase current & voltage symmetrical, etc., among which keeping the voltage and frequency invariable is the most important point.

To hold the frequency constant is a problem of mover speed regulation, while to retain the voltage stable is to control excitation voltage or current. The solutions that are now widely adopted for these two control problems are classic PID controller. But even for a well-tuned PID controller, according to experiences of marine technicians, it possibly wouldn't be suitable for all situations without re-tuning parameters adaptively. For example, during the transient process of a big load commutation, unexpected oscillation with big amplitude perhaps will appear without damage the stability of the system [3] [4]. It would make technicians feel easier if a mechanism exists to detect the coming variation of system performance and help the controller to get ready for it.

To realize this idea, a research project, known as "research

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on control methods for onboard electrical network", is now carried on. This project is dedicated to work on a novel control methodology, combining Gain Scheduling Control with intelligent decision methods, for marine electrical networks. When the topology of the electrical network changes, perhaps be a consequence of load switching, intelligent supervision block will detect this variation and send some information to gain scheduling controller as scheduling variables to assist it to pick up the most suitable control strategy to keep the performance of power system in both steady states and transient processes.

Be one part of work of this project, this paper is focused on building a framework for marine power station. Based on this framework, further problems, such as topology supervision and gain scheduling control, are researched on. This paper is organized as following: the first section is a brief introduction about the motivation; the second section is focused on modeling for different parts of a marine power station; section three is the simulation of single alternator set; then the next section is about the implement of two generator sets auto-parallel; the last part is to discuss some issues in the simulation and to make conclusions.

II. MODELING FOR MARINE POWER STATIONS

A typical marine power station mainly comprises several generator sets, which consist of synchronous alternators, diesel engine movers and excitation systems, main switch board, an emergent generator set, emergent switch board, load control panel and different kinds of loads.

A. Synchronous Alternators

Three phase salient-pole synchronous machine is the most widely used alternators onboard, whose electrical dynamics could be presented by 5^{th} order differential equations [5], which take into account the dynamics of the stator, field, and damper windings in dq frame, as following:

$$\begin{cases} V_d = R_s i_d + \dfrac{d}{dt}\varphi_d - \omega_R \varphi_q \\ V_q = R_s i_q + \dfrac{d}{dt}\varphi_q + \omega_R \varphi_d \\ V_{fd} = R_{fd} i_{fd} + \dfrac{d}{dt}\varphi_{fd} \\ V_{kd} = R_{kd} i_{kd} + \dfrac{d}{dt}\varphi_{kd} \\ V_{kq1} = R_{kq1} i_{kq1} + \dfrac{d}{dt}\varphi_{kq1} \end{cases} \tag{1}$$

Where:

$$\begin{cases} \varphi_d = L_d i_d + L_{md}(i_{fd} + i_{kd}) \\ \varphi_q = L_q i_q + L_{mq} i_{kq} \\ \varphi_{fd} = L_{fd} i_{fd} + L_{md}(i_d + i_{kd}) \\ \varphi_{kd} = L_{kd} i_{kd} + L_{md}(i_d + i_{fd}) \\ \varphi_{kq1} = L_{kq1} i_{kq1} + L_{mq} i_q \end{cases} \tag{2}$$

Where V, i, R, L, φ and w are voltage, current, resistance, inductance, magnetic flux and angular velocity, respectively. The subscripts R and S stand for rotor and stator quantity; m is magnetizing inductance; f and k are field and damper winding quantity.

The mechanical equation is:

$$J\frac{d}{dt}\omega_R = T_m - T_e \tag{3}$$

Where J is the total moment of inertia of machine; T stands for torque. The subscripts m and e indicate mechanical and electromagnetic quantity.

It will be more straightforward and could simplify the calculation when convert rotor parameters to dq frame by formatting all variables in above equations in Per Unit (pu) system. For stator circuit, base values of all parameters are nominal values; while for rotor circuit, the situation is more complicated and the calculation for their base values should satisfy the following requirements: (1) Mutual inductances matrix in pu among armature, field and damping windings should be reversible; (2) Mutual inductances in pu between stator and rotor circuit of both axes should be the same.

In pu system, if the frequency of the stator equals to the base value, the winding's reactance value equals to the inductance value, and transient reactance & subtransient reactance also equal to the corresponding inductance values. Thereby, the reactances are used to present the synchronous generator's parameters instead of inductances.

To determine the values of inductances and time constants for a real synchronous machine, no-load, short-circuit and other frequency response experiments could be carried out by following approaches specified in [6] and [7].

B. Diesel Engine with Speed Governor

Usually, for a diesel engine, according to its torque-speed characteristic which is shown in Fig. 1, the rotating speed is easy to be interfered by the changing of torque, namely, a small commutation of active load will cause comparatively bigger change of the rotating speed of generator set, and result in the variation of frequency, which is an important parameter that should be maintained as a constant in marine electrical network. Therefore, the speed of diesel mover should be regulated, by controlling the quantity of fuel supply, according to the active power demand from load.

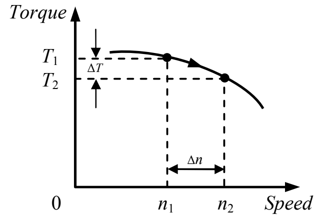


Fig. 1. Diesel engine torque-speed characteristic

The diesel speed governor now being used could be mainly categorized into two types according to their speed measurement methods and controllers: mechanical one and electronic one. The mechanical governor is traditional and employs centrifugal flyweight, levers and other mechanical components to detect the speed and control the fuel supply to the diesel. Due to some shortcomings exist inevitably in mechanical systems, such as serious inertial time delay, big friction and low sensitivity, this kind of governor, although was widely adopted in different situations, is getting less used. Be a substitution, electronic governor was developed rapidly in last decades. This kind of governor makes use of non-touch magnetoelectric sensors to detect the rotating speed and its control part is a PID controller realized by analog or digital circuit.

By considering the importance of mechanical type and making the simulation results easy to compare, both above two types of governor were adopted in our simulations: a basic electrical network platform was built by using mechanical governor, and when gain scheduling controller was designed, electronic one with PID controller was adopted.

The mathematical model for diesel engine with mechanical governor is chosen from [8] and [9], which is shown in Fig. 2. In this model, the controller is modeled as a second order system and the actuator is modeled as a three order system with an integrator included. The diesel engine is modeled as a pure delay. These models were obtained by system identification, and the gains & time constants were adjusted until a reasonable match was obtained between the model and the results from field measurements of generator speed during motor starting.

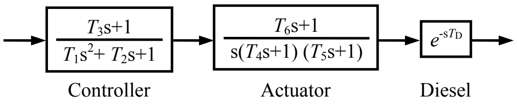


Fig. 2. Models for diesel Engine with mechanical governor

The difference between mechanical and electronic governors locates on the speed measurements and controllers. Thereby, in our simulations, the mathematical model for latter one was obtained by replacing the controller in Fig. 2 with a PID controller. The parameters of PID controller were adjusted until reasonable simulation results were gotten by comparing with the system performance of Fig. 2.

C. Excitation Systems

The function of excitation system is to regulate alternator terminal voltage and control the reactive power distribution among paralleled machines. Because of armature reaction, alternator terminal voltage will fluctuate with the change of inductive or capacitive load. Accordingly, Automatic Voltage Regulator (AVR) is necessary to control the excitation voltage to keep the alternator terminal voltage as a constant.

There are three types of different excitation systems [10]:

1) Direct current commutator exciters

This kind of excitation is a DC generator which generates direct current to supply alternator. Because the commutators inside the DC machine bring arc spark inevitably and the spark will damage insulation resistance and generate electro-magnetic interference, few new synchronous machines are being equipped with this type of exciters.

2) Alternator-supplied rectifier excitation systems

This excitation system uses an AC alternator and either stationary or rotating rectifiers to produce the DC field requirements. The stability of this type exciter is high, and its response speed is fast. Consequently, it is widely used in large capacity generator systems.

3) Static excitation systems

In this kind of excitation systems, voltage (or current), supplying for the generator field, is taken directly from generator terminals or electrical network through transforms and controlled or non-controlled rectifiers. This type of exciters has a broad application in many situations.

Phase compound AC excitation system, which utilize both current and voltage sources (generator terminal quantities) to comprise the power source, is a widely used marine exciter, which takes advantages from the latter two types of excitation system mentioned above. The AVR of this excitation system comprises phase compound circuit, voltage error detection circuit, voltage error magnify circuit, power source, synchronous control circuit, phase control circuit and thyristor rectifier circuit. The model for this kind of excitation system is shown in Fig. 3 [11].

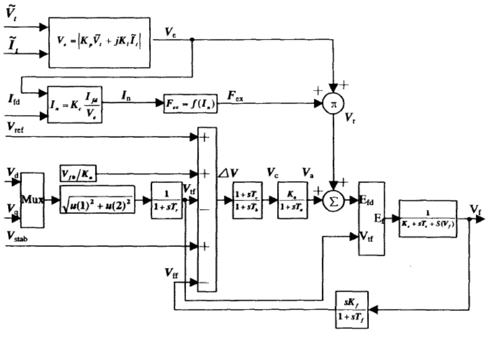


Fig. 3. Phase compound AC excitation system

D. Marine Loads

In the marine power system, more than 80% of load is driven by induction motors, whose dynamic characteristics have an obvious influence on the transient process of power system. Besides, side thruster, rudder servo system, numerous different kinds of pumps, etc. are all typical and power consuming loads.

Although the number of sorts of load is multitudinous, most of them are inductive and could be simplified, at least in the preliminary research stage, as parallel resistances, inductances and capacitances.

III. SIMULATION OF SINGLE GENERATOR-SET

The simulation is implemented in Simulink environment of Matlab by using SimPowerSystems Toolbox, which has libraries contain models of typical power equipments, such as machines, power source, transformers, lines, and electronics, etc., and could facilitate building system models.

The simulated salient-pole alternator is rated at 3.125MVA nominal capacity; 2,400V nominal line-to-line voltage; 60Hz frequency; and 2 pairs of pole (this configuration is extracted from a Simulink Demo named “Emergency Diesel-Generator and Asynchronous Motor"). The model of diesel engine mover is built according to Fig. 2; and the model of excitation system is a block from "Machines" library, the same place where synchronous machine block is located in. After connecting these parts together, the simulation block diagram is shown in Fig. 4, and the blocks inside "Diesel Engine Speed & Voltage Control" subsystem are shown in Fig. 5.

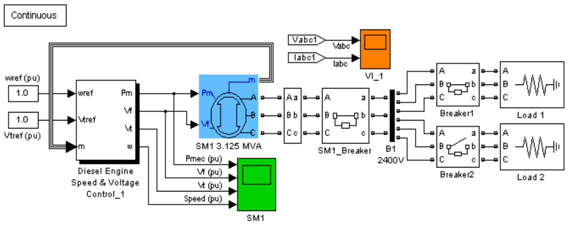


Fig. 4. Single alternator-set simulation diagram

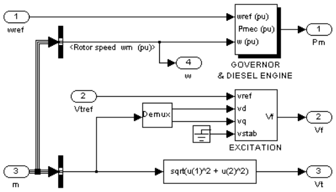
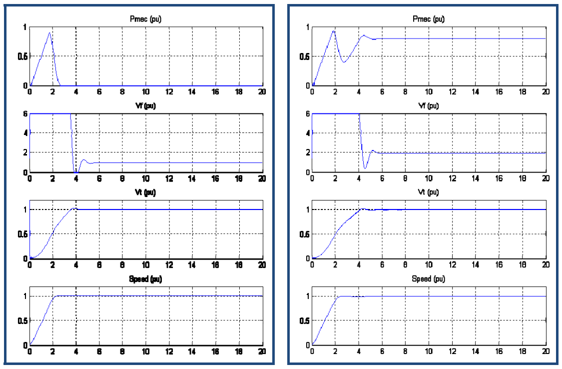


Fig. 5. Diesel Engine Speed & Voltage Control subsystem

When the references of rotating speed and terminal voltage are set to 1 pu, the results of synchronous machine start without and with load are shown in Fig. 6.



(a) no-load (b) nominal load

Fig. 6. Parameters plots of alternator-set start

In Fig. 6, subplot titled 'Pmec' shows mechanical power supplied by mover engine; 'V_f' indicates the field voltage from excitation system; 'V_t' is the RMS of terminal voltage of alternator; and 'Speed' is the rotating speed of machine set during the simulation.

It could be seen from the figures that the alternator came into steady working status after around 6 seconds from start time; the stable values of input mechanical power and field voltage depend on load demand: if no-load is connected, mechanical power was kept in a very small value to balance only the resistance torque from friction, and field voltage is equal to the nominal value; while if an RL load is connected, the demand for active power increased, so more power was offered by the diesel engine, and high excitation voltage was necessary to counteract the influence of armature reaction to hold on the terminal voltage.

If a load commutation happens, a big asynchronous starts for instance, alternator terminal voltage and frequency will begin to fluctuate inevitably [12]. Fig. 7 shows the dynamic process of terminal voltage when a load with 0.4 lagging power factor was connected to alternator at 10 second without retuning the controllers' configuration.

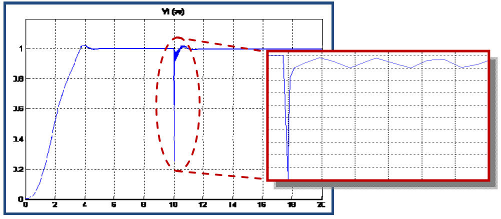


Fig. 7. Terminal voltage plot when load commutation happened

It is obvious to see that the terminal voltage dropped suddenly with big amplitude and vibrated before coming into stable again. According to «Rules for Classification of Sea Going Steel Ships» [13], we had:

"*For AC generating sets under no load conditions, when the generator is driven at rated speed, giving its rated voltage, and is subjected to a sudden change of symmetrical load within the limits of 60% of the rated current and the power factor not exceeding 0.4, the voltage is not to fall below 85% or exceed 120% of the rated voltage.*"

Accordingly, the dynamic process during load commutation didn't satisfy the requirements, which indicates that during the transient process, the configurations of controllers need to be improved in some cases.

IV. SIMULATION FOR PARALLEL ALTERNATOR-SETS

Usually, more than two alternator-sets are equipped on ships to compose the main power source for marine power station. The advantages of doing in this way are prominent: the number of online generators will change according to the power demands from the loads, which could decrease the power usage cost; while in case that malfunctions happen in one generator set, other generator sets could replace its role to tolerant this fault.

In normal case, if the output power of a generator reaches 80% of its nominal capacity, the second one need to be started and paralleled to the electrical network. When parallel action is performed, the terminal voltages, frequencies and initial phases of these two machines should be same to guarantee this operation wouldn't bring much impulse current to the system. However, sometimes it is difficult to strictly satisfy all of them. In case that Automatic Parallel Device (APD) fails or if no APD is equipped like in some old ships, Manual Accurate Synchronization Paralleling (MASP) [14] is an often used method by marine electrician. In such cases, the electrician observes different gauges (for voltage, frequency and phase error) or alternate flashing lamps and press down the parallel button by hands at a special time. Obviously, this isn't an accurate way to guarantee those criteria.

On the other hand, actually, a certain scalar of impulse current, which is within the range that an alternator allows, would help the stand-by machine to accelerate the process of synchronization with the electrical network. Consequently, some compromises are made to those three requirements. Generally speaking, when parallel is carried on, the maximum permissible error for voltage is within 10% of nominal value; for frequency it is 0.5Hz; for initial phase it is 15 degrees. And the impulse current less than double nominal value is under the endurance range of an alternator.

As mentioned above, the MASP is operated by an electrical engineer manually at special times when the synchronous meter (or other devices) indicates that the error of instantaneous voltage is close to zero. To simulate this MASP operation, the amplitude and angle of pulsating voltage, the fundamental component of vector difference of instantaneous voltage between stand-by & online machine, is adopted.

The architecture of two generator sets system implemented in Simulink is shown in Fig. 8, and the block diagram inside the paralleling time control subsystem is shown in Fig. 9.

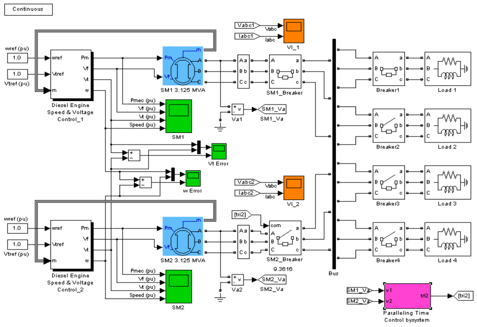


Fig. 8. Simulation blocks for two generator-sets

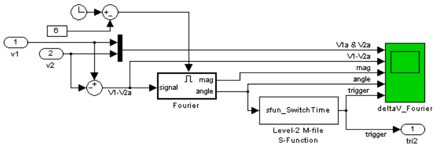


Fig. 9. Block diagram inside the paralleling time control subsystem

In Fig. 8, the upper synchronous machine (SM1) was working with nominal load and the lower one (SM2) was standing by. Terminal voltages of phase "a" for both generators were measured and notated as V_{a1} and V_{a2}. Assure the difference of phase and terminal voltage between SM1 and SM2 are zero; the maximum value of voltage amplitude is V_m; angular frequency for SM1 and SM2 are w_1 and w_2 respectively. Hereby, the vector difference of V_{a1} and V_{a2} is:

$$\Delta V = V_m(\cos w_1 t - \cos w_2 t) = -2V_m \sin\frac{w_1 + w_2}{2}t \sin\frac{w_1 - w_2}{2}t \quad (4)$$

Perform Fourier transform to (4) to filter harmony and to get the amplitude and phase of pulsating voltage. The simulation results are shown in Fig. 10.

From Fig. 10, it could be seen that the period of pulsating voltage, fundamental voltage namely, is around 4.9 seconds, which indicates that the frequency difference is around 0.2Hz. At times that the phase crosses zero from positive to negative value, the amplitude also reaches the minimum, indicating that the phase difference of SM1 and SM2 is zero. Thus, paralleling could be executed at these time points.

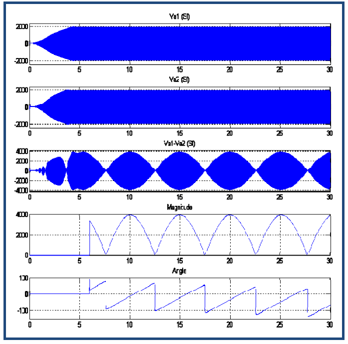


Fig. 10. Plots of amplitude and phase of pulsating voltage

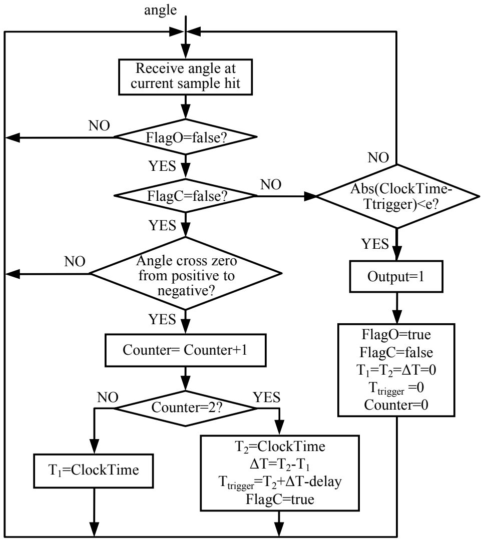


Fig. 11. Routine flow chart inside the s-function block

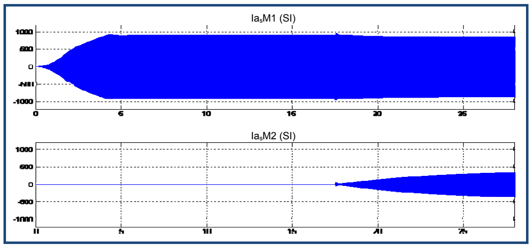


Fig. 12. Terminal currents of SM1 & SM2 in parallel simulation

The switching time of SM2 is controlled by an external trigger signal generated from a Level-2 M-file S-function block. If physical delay of switch is taken into account, the trigger process inside the s-function block could be presented in Fig. 11.

The above pulsating voltage based paralleling simulation assured that phase and terminal voltage differences between SM1 and SM2 are zero. Actually, even getting rid of this assumption, the above parallel method is still tenable.

The simulation results of paralleling are shown in Fig. 12, from which it could be seen that the impulse current during the parallel process is pretty small.

V. DISCUSSIONS

A. *Simulation precision setting*

Relative tolerance and *absolute tolerance* are two important parameters used to compose *acceptable error*, with which *local error* (calculated by *solvers* at the end of each simulation time step) is compared in each sampling time hit. The values set to these two parameters have a big influence on the simulations results. For the simulations in this paper, some unexpected phenomena, such as voltage high frequency & low amplitude oscillation in steady states, could be improved by setting these two error tolerances to smaller values. In some extreme cases, the setting values of them will topple down the results, whatever the *solver* is. For example, the impulse current in the parallel simulation will be several times larger than the value presented in Fig. 12 if the error tolerances were not set to be small enough. Nevertheless, if these two values are set to be too small, less than 10e-7 for example, the simulation process will be pretty slow and memory errors sometimes happen.

B. *Voltage spines*

In the alternator starting simulations, before the terminal voltage and speed came into steady state, voltage spine often appears in the plot of terminal voltage. An example is shown in Fig. 13. These spines are statistics-like and always have very high amplitude (from several to 10e4 times 1 pu) and short duration (less than 10e-4 seconds). They are related with not only the values of relative tolerance and absolute tolerance, but also with the configurations of machine and excitation system. The mechanisms of its appearance need further research.

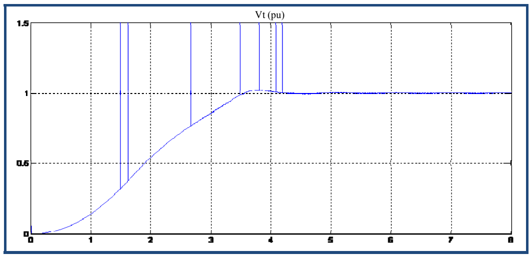


Fig. 13. An example of voltage spine appeared in terminal voltage

C. *Initial value of alternator rotating speed*

For the simulations in this paper, when an alternator starts, its rotating speed increases from a value near zero to nominal value, which looks realistic. This is implemented by modify the value of a 'Constant' block (named as 'nom. speed' and located inside the 'SM_mechanics' subsystem of Synchronous Machine block) from 1 to a very small positive value. Without doing this, the machine will start from nominal speed in any case.

VI. CONCLUSION

This paper presented the work about the modeling and simulation for onboard power systems. The modeling of four main parts, including models for synchronous alternator, diesel engine mover, excitation system and loads, were specified after the motivation introduction about the project. SimPowerSystems Toolbox of Matlab was adopted to implement these models and carry out simulations about single generator set start, load commutation, and two generator sets parallel. Some simulation results, as well as several issues that need to be taken care of during the simulations were elaborated.

Building a framework for marine power system is just the basis of further research for our project. Seeking working points that system performance couldn't be satisfied with existing controllers and optimizing controller configurations for the corresponding situation are the missions we are carrying out. Furthermore, trying to detect the variation of topology of electrical network for gain scheduling controller and making some predictions about the coming system performance are the further work with more challenges.

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