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Decentralized Control of Power Generation Sources in Naval Ships as Inverter-based Microgrid

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Abstract

To have stable network in a naval ship with inverter-based power system, proper load sharing plays key role. In addition, decentralized control to share loads in naval ships can be an approach to raise reliability of system especially in battles. Droop control has been utilized as an effective approach to share loads respect to VSCs capacity. In this paper, a novel method named Frequency Tracking is introduced. By applying Frequency Tracking on conventional droop control, electric loads inside a naval ship are shared on Voltage Source Converters more accurately and in a decentralize way. Simulation results in PSCAD are confirmations of proposed method in naval ships in order to perform correctly.

Keywords: Decentralized Control, Electric Ship, Load Sharing, Microgrid, Voltage Source Converters

1. Introduction

In naval ships, electrical energy utilization is rising day by day and in defense systems, fight systems, propulsion systems, automation systems and various kinds of electrical loads it is observed. Medium Voltage (MV) DC power systems in the structure of electric ships can be introduced as one of the interesting topics in recent researches[1]. Applied facilities in naval ships such as electric guns, high power sensors, radars, electric launcher and etc. need power system in order to supply required electrical energy. By using electric systems, In addition to optimization in energy consumption, flexibility and ease of using equipment and efficiency increase can be achievable[2]. Required electrical energy in naval ships structure is provided by synchronous generator and gas turbine as main prime mover or diesel generator as auxiliary prime mover[1]. Naval ships in supplying inside electric loads without bulk power system perform as an islanded Microgrid. Microgrid is defined as a small scale power system including various electric loads, heat loads and Distributed Energy Resources (DER) among renewable energy resources. In bulk power system overview Microgrids are identified as a cell with control capability and in consumer overview Microgrids are considered as a high reliable network, low loss and high efficient network in power generation[3].

One of the advantages of using power system in naval ships as an islanded Microgrid is utilization of electric propulsion systems inside it. In addition to elimination of mechanical power transmission systems, such as gearbox and shaft, it is possible to achieve maximum flexibility in design and due to lack of dependency between ship velocity and turbine velocity, achieving maximum efficiency in mechanical and electrical system is feasible[4,5]. MV DC power system utilization in naval ships beside energy storage and drives for controlling electric motors in propulsion systems has various advantages such as better maneuverability, less air pollution in harbors and reduction of emitted noises from ship in critical situation. G. Snitchler[6] has considered design of propulsion systems.

Load sharing in electric ship including propulsion systems and military equipments with high power demand has been taken into consideration in recent years[7,8]. In autonomous power system of electric ships as islanded Microgrid the responsibility of stabilizing

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frequency and voltage is on Voltage Source Converters (VSCs). Different methods have been introduced in centralized and decentralized control of VSCs in islanded Microgrid[9]. Centralized and integrated control in load sharing and supplying electric loads in naval ships have low reliability and would be limitative. It is due to the probability of damage in battles and losing whole electric network inside ship.

In this paper, in order to raise reliability of electric networks in ships in supplying loads, using VSCs and achieving maximum autonomy of them are discussed. Load sharing among VSCs by novel method named Frequency Tracking (FT) are introduced that in ongoing parts of this paper the introduction of method and its advantages are considered. In section two, load sharing is discussed and by introducing FT and its terms in third section the environment to apply proposed power system for naval ships by introduced control system in section four is provided. In fifth section, conclusion and sum up are conducted.

2. Load Sharing and Droop Control

Electric loads should be shared on power generation units in order to have stable network. In centralized control of Microgrids, it is necessary to have communication lines between VSCs and central controller to process and analyze input signals and sent output signals to converters[10]. This matter causes complexity of control system in power system inside electric ships, therefore, decentralized control of VSC units as an effective method to tackle disadvantages of centralized control has been presented[11]. In under-study naval ship, which is considered as inverter-based islanded Microgrid, sensitive and high priority loads are supplied by power electronic interfaces. In addition, propulsion system of electric ship is attached to MVDC bus separately. In an islanded Microgrid all VSCs are in charge of maintaining frequency and voltage in predefined ranges.

In order to share loads on power electronic interface units, active power / frequency (P / f) droop control has been applied to have similar structure of Microgrid as conventional power systems[12]. On the other hand, to control voltage and share reactive power on generation unit's reactive power / voltage (Q / V) droop control has been presented as practical approach[10]. In other word, the drop characteristic in P / f is the natural relation between active power and frequency and drop characteristic in Q / V is considered as the effect of voltage on reactive power sharing. Figure 1 depicts drop characteristic of three VSC units in a Microgrid. Complete set of equations in droop control and load sharing on VSCs have been presented in[13].

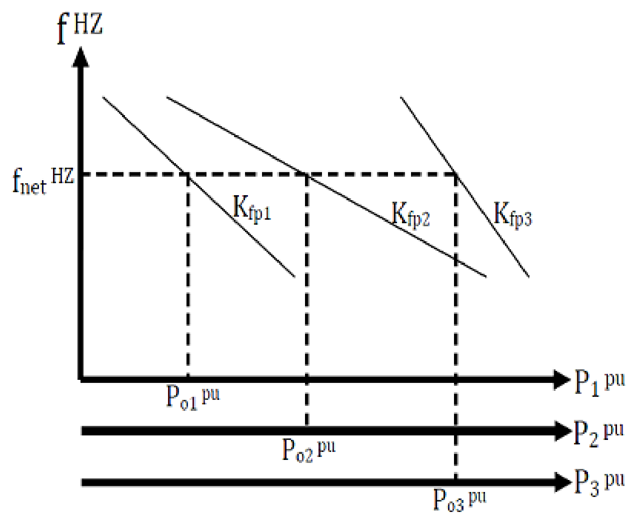

Figure 1. Drop Characteristic of Three VSC Units with Decentralized Control.

In this paper by introducing novel method, in addition to elimination sensitivity of control system to the structure of communication lines and network, required active power is shared on generation units inside Microgrid by fast and acceptable dynamics according to their nominal capacity. To better understand the performance of droop control and getting familiar with variables in Figure 1, parallel operation of VSCs is addressed. Firstly, a simple network including two VSC units and a common load is taken into account. Figure 2 illustrates mentioned network.

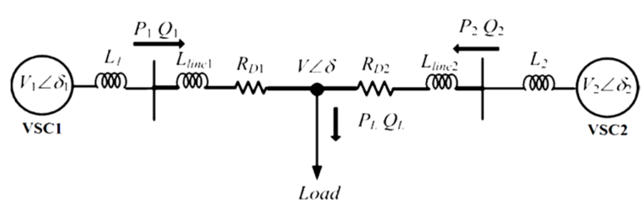

Figure 2. Configuration of Supply System in Electric Ships as a Microgrid to Apply Control System.

In Figure 2, each VSC unit supplies loads according to its nominal capacity. To apply droop control on VSCs, equation 1 is introduced as main equation:

$$f_i^* = f_n + K_{fpi}(P_n - P_{01}) \quad (1)$$

In equation (1) as illustrated in Figure 1 $\mathbf{f_n}$ is the nominal frequency of the network in nominal operation point of each generation unit ($\mathbf{P_n}$). $\mathbf{K_{fpi}}$ and $\mathbf{P_{oi}}$ are active power droop coefficient and output active power of VSC_i respectively. It should be noted that $\mathbf{K_{fpi}}$ is a small positive number and it is in respect to the VSC_i capacity. Droop coefficients of active and reactive power in VSCs are calculated according to allowed change of frequency and voltage. Equation (2) shows how $\mathbf{K_{fpi}}$ is chosen according to mentioned changes:

$$K_{fpi} = \frac{\Delta f}{\Delta P_{oiMax}} \quad (2)$$

It should be noted that Equation (2) refers to master unit that is introduced in ongoing parts. The value of coefficients play major role in stabilizing electric ship power system including VSCs[14]. In order to have dynamic analysis on droop control and stability of network in load sharing inside inverter-based networks, C. K. Sao[15] has been extracted essential equations in this matter. To summarize, although droop control causes network frequency drop slightly, it eliminates exchanging control signals through communication line between VSCs and it is utilized to share loads on generation units[16].

3. Frequency Tracking (FT) Method and Load Sharing in Electric Ships

Before conducting mathematical equations of FT, it is useful to refer Figure 2. By assuming that two VSC units have different nominal capacity and naming unit 1 and 2 as master and slave respectively, the conventional droop control system has been applied to the mentioned Microgrid in Figure 3.

Parameters in Figure 3 are:

- Kfp_1: Droop coefficient chosen for master unit.
- P_1: Output active power of master unit.
- P_{1n}: The nominal active power of master unit.
- f_n: The nominal frequency of network.
- f_1: Generated frequency of master unit.

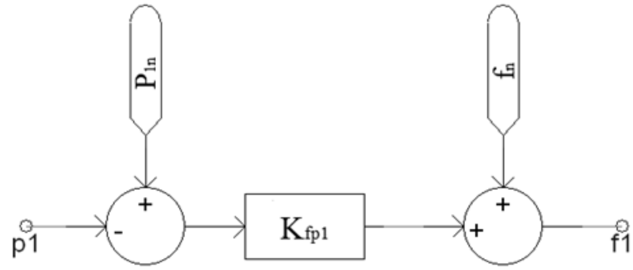

Figure 3. Applied Control System for Master Unit in PSCAD.

In other words, VSC no. 1 generates its nominal active power with the nominal frequency (60HZ). In FT other units are forced to track the frequency of master unit. Therefore, control system structure should prepare this issue. In order to achieve mentioned goal, by utilizing a PI controller in control system of second VSC unit frequency error between two VSC units is eliminated. Figure 4 illustrates applied PI controller in control system generally.

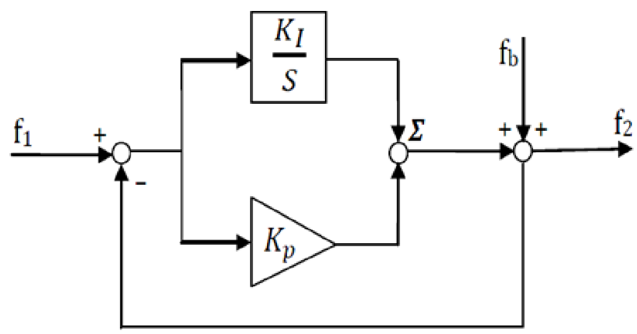

Figure 4. Complementary Proposed Control System for Slave Units.

- f_1: Generated frequency of master unit after applying droop control.
- f_b: Defined frequency for slave unit after applying droop control.
- f_2: Directed output frequency to slave unit.

As mentioned in previous sections, in order to stabilize network it is necessary to have equivalent frequency in output power of VSC units. In ships with VSC units and electric loads, the frequency and voltage of each unit cannot be imposed by central controller and this is due to decentralized control that is applied to system. Therefore, a suitable approach should be chosen that controls VSC units with decentralize structure and in addition to stabilize network frequency, shares electric loads on power generation units precisely. Figure 5 depicts FT function for second unit in Microgrid with structure in Figure 2.

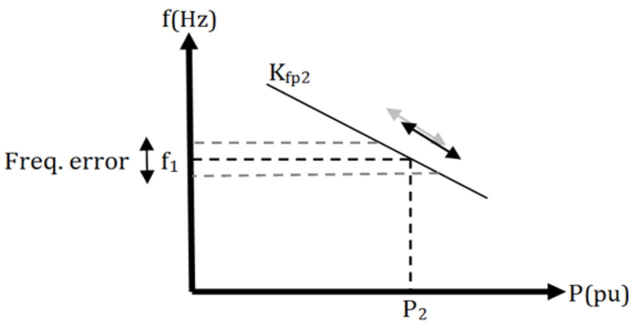

Figure 5. PI Controller Function in Stabilizing Frequency.

In proposed method, generated frequency of each VSC unit comes close to master unit generated frequency in order to have fixed and equivalent frequency in electric ship's network. It is done by a PI controller. Generally, PI controller changes generated frequency of slave VSC instantly and frequency error between units becomes near to zero in stable operation. In ongoing parts advantages of proposed method and its superiority to other methods are introduced.

By considering Equation (1) and control structure of FT, generated frequency by second unit according to output active power can be defined by Equation (3).

$$f_b = f_n + K_{fp2}(P_{n2} - P_{o2}) \tag{3}$$

According to the block diagram illustrated in Figure (4), Equation (4) indicates generated frequency by second unit respect to changes in generated frequency by master unit and droop characteristic of second unit.

$$f_2(s) = \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \text{ x } f_1(s) + \frac{1}{1 + k_p + \frac{k_i}{s}} \text{ x } f_b(s) \tag{4}$$

In Equation (4) K_p and K_i are proportional and integrator coefficients of PI controller respectively.

According to Equation (4), the proposed control system has a pole on the left side of the imaginary axis. As a result, the first order system prevents instability and fluctuating at the moment of load changing. Eigen values of the control system can be calculated by Equation (5):

$$\lambda = -\frac{k_i}{1 + k_p} \tag{5}$$

Therefore, Integrator in control system for stabilizing Microgrid is necessary when changes occur.

To better introduce transfer function, we rewrite Equation (4) as Equation (6).

$$f_2(s) = \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \text{ x } [(f]_n + k_{fp1}P_{n1}) - \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \text{ x } [(k]_{fp1}P_{o1}(s)) + \frac{1}{1 + k_p + \frac{k_i}{s}} \text{ x } [(f]_n + k_{fp2}P_{n2}) - \frac{1}{1 + k_p + \frac{k_i}{s}} \text{ x } (k_{fp2}P_{o2}(s)) \tag{6}$$

In Equation (6), the generated frequency signal by the second unit for P_{o1} and P_{o2} as input signals for control system is shown.

In the system that consists of two units, total requested active power in network is sum of each unit's active power, as a result.

$$P_l = P_{o1} + P_{o2} \tag{7}$$

So with substitution Equation (7) in Equation (6), the frequency change in unit 2 for load changes in the network and unit 1, can be calculated as Equation 8.

$$f_2(s) = \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \text{ x } [(f]_n + k_{fp1}P_{n1}) - \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \text{ x } [(k]_{fp1}P_{o1}(s)) + \frac{1}{1 + k_p + \frac{k_i}{s}} \text{ x } [(f]_n + k_{fp2}P_{n2}) - \frac{1}{1 + k_p + \frac{k_i}{s}} \text{ x } (k_{fp2}[(P]_l(s) - P_{o1}(s))) \tag{8}$$

To show power change within network better, step function has been used that represents pulse loads in structure of ships. As a result, required active power changes from P_{L1} to P_{L2} suddenly. Therefore, generated active power by first unit–master–changes as step function according to drop characteristic. Step change in active power demanded by network and generated power by first unit in S domain are shown in Equation 9 and 10 respectively:

$$P_l(s) = \frac{\Delta P_l}{S} \tag{9}$$

$$P_{o1}(s) = \frac{\Delta P_{o1}}{S} \tag{10}$$

A change in output frequency in second unit during stable operation is directed according to Equation 11.

$$\Delta f_2(t) = -[(k]_{fp1} \text{ x } \Delta P_{o1}) \tag{11}$$

By considering Equation (11), right site if the equation represents frequency change in master unit. Therefore, frequency change in second unit is exactly coincided with master unit and there is no frequency error in stable operation in network.

In addition, in stable operation, for second unit f_b and f_2 are equal to f_1. As a result according to Equation (2) it is shown that.

$$\triangle f_2(t) = -[(k)_{fp2} \,\mathrm{x}\, \triangle P_{o2}] \qquad (12)$$

By analyzing Equation (11) and (12) it is proved that.

$$[(k)_{fp2} \,\mathrm{x}\, \triangle P_{o2}] = [(k)_{fp1} \,\mathrm{x}\, \triangle P_{o1}] \qquad (13)$$

Equation (14) is the provision of load sharing on power generation units that many references have addressed this issue by different approaches[15,17].

4. Simulation Results

At first the schematic structure of power system in naval electric ship has been shown in Figure 6. In this figure, electric energy generation approach and equipment places in ship power system have been specified.

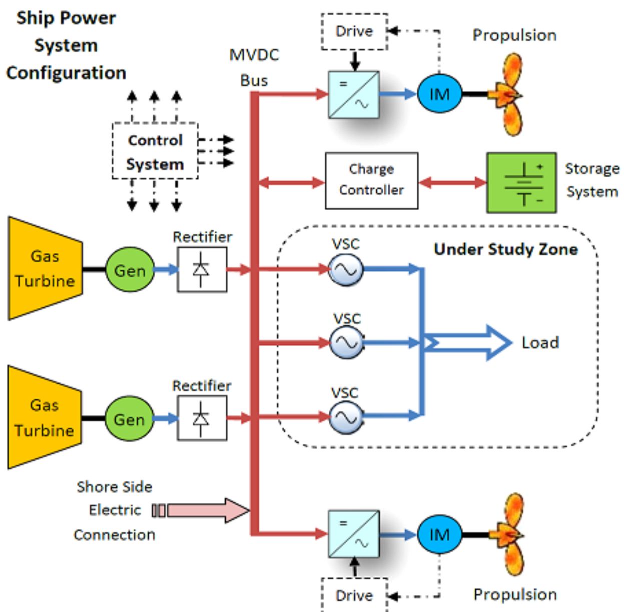

Figure 6. Power System Structure in Naval Electric Ship.

As illustrated in Figure 6, needed electric energy is provided by two gas turbines that rotate synchronous generators. Then after rectifying, synchronous generators are connected to MVDC bus. The necessity of having two gas turbines as main and auxiliary is due to raise reliability and distribute energy generation system in ship to avoid centralization. In addition, by losing one generation unit or in maintenance schedule, second unit plays vital role to supply needed electric energy.

Electric propulsion system is connected to DC bus trough appropriate drive that in ongoing parts advantages of having electric propulsion system and its connection to DC bus will be discussed.

One of the advantages of electric ship, which has been shown in Figure 6, is the ability to connect to the bulk power system in shore and harbor. On the one side, by using electric connection in shore and harbor during entering ships, the pollution caused by ships will be reduced dramatically[18]. On the other side, electric ship power system is completely testable and analyzable during berthing. In order to analyze advantages of electric connection of ship to the bulk power system, Y Khersonsky[19] would be proper source. It should be noted that the existence of energy storage system in electric ship structure, either in normal operation or in berthing, plays vital role to raise ship's performance. Information about power system standards in shore and the connection methods of electric ship to bulk power system have been investigated in[20].

Under study zone, which composes of three voltage source converter to supply various military or civilian electric loads, is taken under consideration and analysis to have decentralized control with maximum autonomy. As mentioned in previous sections, the reliability of system will be raised by parallel operation of VSCs and this issue would be considerable in the case of losing one power generation unit in maintenance schedule, fault or damage in clashes. The proposed control system, in addition to share loads on VSCs respect to their nominal capacity, brings stable network with fast and acceptable dynamics beside decentralized control.

4.1 Under Study System

Figure 7 shows under study system included three VSCs, communication lines, centralized electric loads and interface Inductance of converters.

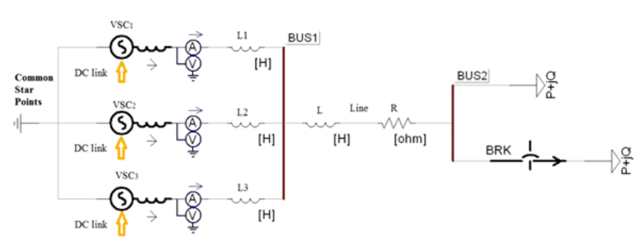

Figure 7. Under Study System in an Electric Ship in PSCAD.

To better examine performance of network in changing electric load or losing one generation unit the capacity of each unit has been defined different from the other one and the interface inductance of converters are also set with different values. Communication lines inside the network are the equivalent of lines impedance from power generation units to loads. Obviously, the communication lines in electric ship are short. Therefore, the value of X / R is very low and it can be neglected. However, to have more real model and results in simulation, communication lines have been modeled as dominantly resistive lines. Table 1 shows the value of elements within the network. In presented model, first unit (VSC1) is known as master and other units are slave.

Table 1. Network Figure 7 Elements Value

P_{n1}^{KW}:	200	L_1^{H} :	0.001
P_{n2}^{KW} :	100	L_2^{H} :	0.0015
P_{n3}^{KW} :	50	L_3^{H} :	0.0012
K_{pf1} :	0.048	Z_{line}^{Ω}:	0.01+j0.001
K_{pf2} :	0.096	f^{Hz} :	60
K_{pf3} :	0.192	V^{v} :	1000
Fixed Load ^{KVA}:	300+j30	Variable Load ^{KVA}:	120+j12

According to Table 1, nominal power of VSC1 is two times greater than VSC2 and also 4 times greater than third unit (VSC3). By considering Equation 14 and using droop coefficient in droop control inside control system structure of electric ship, the droop coefficient for VSC1 as master unit has been chosen 0.048 and to have stable network, decentralized control system and share loads on power generation units respect to their nominal capacity the droop coefficients for second and third units are 0.096 and 0.192 respectively.

Voltage source converters which have been used in mentioned electric ship have been connected to the electric distribution system through interface inductances with set values given in Table 1. Fixed load has been connected to the converters in one point and variable load is connected to the network at specific time and after passing seconds at another specific time will be cut. Generally by using variable load and imposing changes on the network, the performance of electric ship in carrying heavy electric load such as pulse loads with high power demand is examined.

It should be noted that voltage source converters in ship power system are controllable through control signals that impose electricity frequency and voltage magnitude. Therefore, by utilizing FT and droop control on frequency signal of VSCs it is expected to have total active power of network shared on VSCs with acceptable dynamics and exact proportion. In addition, it has been assumed that the needed energy of whole network is always available and steam turbines by rotating synchronous generators make DC bus voltage magnitude constant in its nominal value.

4.1.1 Normal Operation of Under-Study Network

In this part, under-study network within electric ship that is known as islanded Microgrid is controlled by applying proposed control system. Firstly the network operates in normal condition with stable circumstances ant then in the fifth second of simulation one pulse load is connected to the network and after passing five seconds (in the tenth second) this load is cut. Figure 8 depicts the output active power of VSCs to share network loads:

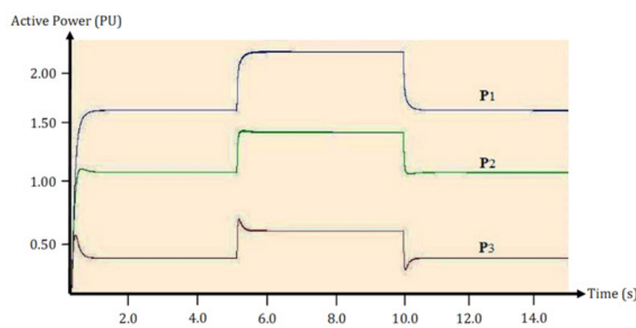

Figure 8. Output Active Power of VSCs in Normal Operation to Share Loads.

As expected, total load of the network including line losses and central loads in electric ship have been shared on VSC units respect to their nominal capacity. It should be noted that in Figure 8, output characteristics of three VSC units have been normalized based on 100^{KVA} apparent power (per unit values). In addition, unit no. 1 and no. 2 transfer needed active power from DC bus to AC bus without any undershoots or overshoots in their output power. Figure 9 shows the output frequency of VSCs after applying droop control and FT.

The aim of utilizing FT in sharing loads on VSCs inside electric ship in first step is stabilizing network. To reach this goal and prepare situation for VSCs to operate in a parallel way, the output frequency of these units should be same without any errors and disparities in stable operation. As it is shown in Figure 9, all units track the frequency of first unit (master) and there is no frequency disparity between units during entrance of pulse load and cutting it in stable operation. By viewing Figure 9 it has been shown that the frequency of all units in eighth second are 59.981^{HZ} with high accuracy. According to standards of Defense Ministry of United States for naval electric ships, in ships type I the frequency disparity with reference value (60^{HZ}) should not exceed 3%[21]. However, the frequency disparity in naval electric ship with proposed control system in less than this percentage.

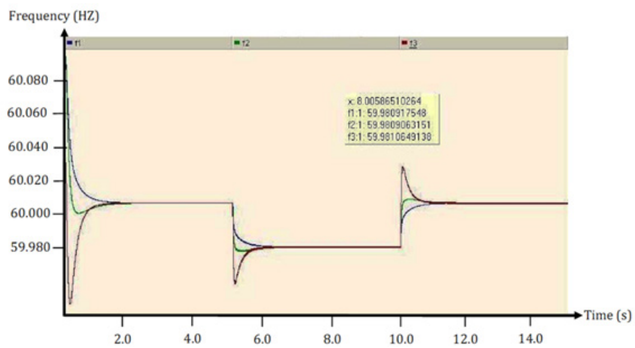

Figure 9. Output Frequency of VSCs in Normal Operation.

Table 2 shows the values of active power shared on VSC units base on 100^{KVA} in eighth second.

Table 2. Shared Active Power on Vsc Units at Eighth Second

P_1^{PU} (t = 8s):	2.12	P_3^{PU}(t = 8s) :	0.59
P_2^{PU}(t = 8s) :	1.43	f^{HZ}(t = 8s) :	59.98

4.1.2 Network Performance during Losing One VSC Unit

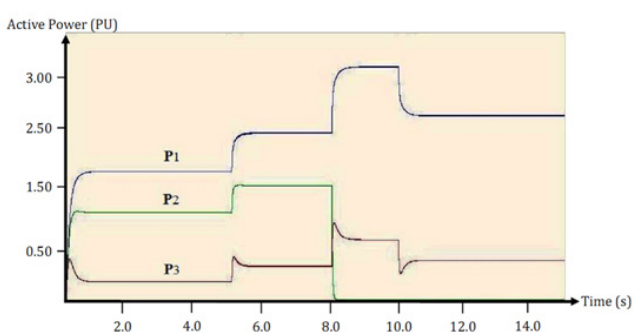

Figure 10. Output Active Power of VSCs in Mentioned Scenario.

In this section, in addition to imposing pulse load on network within mentioned electric ship, at eighth second the second unit is cut from network suddenly and the simulation results will be analyzed. Figure 10 depicts the output active power on VSCs in mentioned scenario with predefined circumstances:

After dismissing second unit, we expect rest of the units share load automatically and independently without any input signals. As it has been shown in Figure 10 the output power of second unit turns to zero in eighth second and the output power of first and third units in eighth second rises suddenly to compensate the portion of power related to dismissed unit in load sharing respect to nominal predefined capacity. Figure 10 shows output power of VSCs in 100^{KVA} base. To analyze output frequency of VSCs according to their operation point in mentioned scenario, Figure 11 is presented.

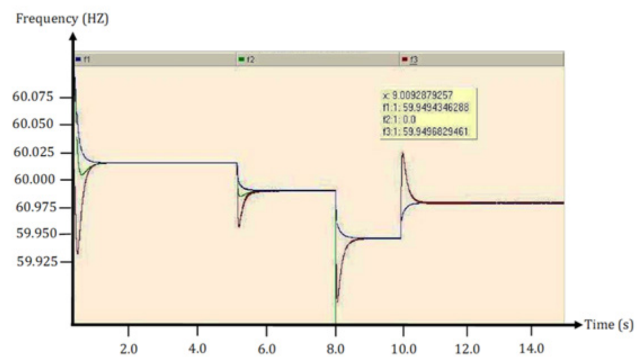

Figure 11. Output Frequency of VSCs In Mentioned Scenario.

By increasing loading on master unit, as it has been illustrated in Figure 11, the network frequency decreases more. According to Table 1, master unit nominal capacity has been set to 200^{KW} and it is supposed that all units are able to supply electric loads beyond their nominal capacity. Therefore, by distancing output power of master unit from its nominal capacity according to droop control, the network frequency will distance from its nominal value. However, in this operation condition of network, the frequency disparity with nominal value (60^{HZ}) is about 0.05^{HZ}that this value respect to mentioned standards is neglected and acceptable. It should be noted that in more complete model, by applying protection systems, overloading will be prevented by load shedding and in this matter priority issues are taken into consideration.

5. Conclusion

In this paper, first of all the novel power systems inside naval electric ships have been introduced and the advantages of using power system within ships to supply electric loads and propulsion systems has been discussed. By considering electric ship structure, it is fine to relate electric ships to islanded Microgrid with ability to connect to bulk power system in harbors. One important matter in inverter-based Microgrids operation is having stable network in islanded mode that has been addressed previously. After going through Microgrids and Electric ships, Frequency Tracking (FT) has been introduced as novel method to have decentralized control over VSCs inside ship power system. One of the advantages of decentralized control and power system structure including VSCs is omitting central controller and the other advantage is information data decrease to process. These advantages cause maximum autonomy for power generation units and at the time of dismissing one or some units, rest of the units with high response time share electric loads among themselves according to their nominal capacity. Beside mentioned advantages, the possibility of increasing capacity of ship power system without making any changes to control system structure can prepare a foundation to increase needed electric demand within naval ships.

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