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Design, Analysis and Comparison of Automatic Flux Regulator with Automatic Voltage Regulator Based Generation System for DC Marine Vessels

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Abstract—The generation system in the dc marine vessel is expected to be comprised of wound rotor synchronous generator (WRSG) which is interfaced with the active front-end rectifier. For such system, WRSG flux and dc voltage at the active front-end rectifier output are controlled independently. WRSG flux is maintained by the field excitation circuit of WRSG for which automatic voltage regulator (AVR) has been traditionally employed. AVR operates by regulating the WRSG terminal voltage, thus demands additional tuned filter for the application in dc marine vessel. This filter increases the size of the generation system along with additional cooling requirements at higher load. With this regard, this paper introduces automatic flux regulator (AFR) based field excitation system where the WRSG flux is maintained directly and is independent of the measurement of the terminal voltage. Small-signal analysis is done to design the control loop of the AFR based field excitation circuit. To verify its efficacy, comparison with the AVR based dc generation system is conducted. The comparison has been done on the basis on control response and marine operation.

Index Terms—DC Bus Voltage Control, DC Shipboard Operation, Excitation System, Flux Estimation, Synchronous Generator.

NOMENCLATURE

C	DC-link capacitor
C_f	Filter Capacitance of the LC filter
i_o	Output dc current of AFE rectifier
θ_p	Reference angle generated by PLL (Phase locked loop)
i_{ds}^p, i_{qs}^p	d - q current of WRSG in PLL reference frame
v_{ds}^p, v_{qs}^p	d - q voltage of WRSG in PLL reference frame

i_{ds}^r, i_{qs}^r	d - q current of WRSG in RRF (rotor reference frame)
v_{ds}^r, v_{qs}^r	d - q voltage of WRSG in RRF
θ_s	Reference angle for stator flux reference frame (SFRF)
i_{Ms}, i_{Ts}	M - T current of WRSG in SFRF
v_{Ms}, v_{Ts}	M - T voltage of WRSG in SFRF
K_{exc}	Gain of Type-ST Exciter
L_s	WRSG stator inductance
L_f	Filter inductance of the LC filter
p	Number of poles of WRSG
R_s	WRSG stator resistance
R'_{fd}	Field winding resistance of WRSG (referred to stator)
R_d	Damping resistance of LC filter
v_{dc}	Output dc-link voltage
X_s/L_s	Synchronous Impedance/Inductance
X_{md}/X_{mq}	WRSG d - q axis reactance
X_{lf}	WRSG field circuit reactance
$\lambda_{ds}^r, \lambda_{qs}^r$	WRSG Flux linkage in RRF
$\lambda_{Ms}, \lambda_{Ts}$	WRSG Flux linkage in M - T axis
ψ_{Ms}, ψ_{Ts}	Flux linkage per second of WRSG in M - T axis
τ'_{do}	WRSG open circuit time constant
τ_{exc}	Time constant of Type-ST Exciter
ω_b, ω_r	Base speed and rotor speed of WRSG

I. INTRODUCTION

In recent years, the paradigm shift in the energy conversion technologies of the emerging marine vessels have witnessed a transition from the ac to dc power systems. This transition to the dc marine vessel is primarily strengthened by the fuel efficient operation of the interfaced diesel generator (DG) running at the optimized speed [1]–[5]. With the requirement of stringent emission control as per the guidelines issued by the International Maritime Organization, such dc power conversion systems in marine vessels are expected to be adopted in the near future [2], [6], [7]. It is further supported by the availability of efficient ac/dc [8] and dc/dc [9] power electronic conversion devices. Thus, the modeling, control and the operation of the dc generation system becomes an important

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aspect for such emerging marine vessels with some of the functional aspects being inherited from the conventional ac generation systems.

The *ac generation system* in the conventional ac marine vessel comprises of the fixed frequency DG to comply with the strict frequency and phase synchronization requirements [10], [11]. On the other hand, DG of the *dc generation system* in dc marine vessel is expected to be interfaced with the active front-end (AFE) rectifier, enabling it to run asynchronously and operate in variable speed according to the load demand. This particular operation leads to the lower specific fuel oil consumption (SFOC) resulting in increased fuel efficiency [2], [7]. It is to be noted that the common control requirements for ac and dc generation system is to maintain the terminal bus voltage while operating the interfaced ac generator (of the DG) within the prescribed flux limits. For the marine vessels requiring higher power, wound rotor synchronous generator (WRSG) might be preferred choice for the interfaced ac generator on account of lower cost, robust design and superior fault current limiting capability which is partially achieved through field de-excitation system [12], [13]. As a result, the external field excitation system of the interfaced WRSG is of substantial importance while designing control framework of the generation system.

A. AC Generation System

In the ac marine vessels, WRSG is generally interfaced with the ac bus [10]. Such cases emulate the control requirements for the isolated ac grid conditions where WRSG terminal voltage i.e. the ac bus voltage is maintained by the voltage regulator based field excitation system and is conventionally known as ‘automatic voltage regulator (AVR)’. The availability and measurement of the sinusoidal voltage at the WRSG terminals have supported the widespread utilization of AVR in the ac power systems, and in traditional ac marine vessels [14], [15]. The functional block diagram of AVR as depicted in Fig. 1 comprises of three basic blocks (a, b & c) for voltage regulation and three advanced blocks (d, e & f) for load compensation and stability of the multi-machine system [15]. AVR compares the terminal voltage of the WRSG against a defined set-point and subsequently varies the field current/field voltage to maintain the desired terminal voltage for different loading conditions. In other words, AVR indirectly controls the flux of the WRSG by directly maintaining the terminal voltage to a speed dependent set-point.

B. DC Generation System: Problem Statement

The control objective of the dc generation system is to regulate the dc bus voltage at the AFE rectifier output while independently operating the WRSG within the prescribed flux limits. Since the WRSG is interfaced directly with the AFE converter, its terminal voltage is influenced by the AFE converter switching voltages and dc-link voltage. Although the

Fig. 1. Functional block diagram of AVR based field excitation control system of WRSG.

Fig. 2. Generator terminal voltage when (a) interfaced directly with the converter and (b) interfaced with the filter inductor.

internal voltage of the generator (e_T) is sinusoidal, it is the terminal voltage (v_T) after the synchronous impedance (X_s) which is of switching voltage type as illustrated in Fig 2(a). Hence, the measurement of the voltage directly at the WRSG terminal would not reflect its performance thus limiting the applicability of AVR for WRSG terminal voltage and flux control. However, AVR can be suitably integrated by filtering out the switching voltage across the WRSG terminal thus enabling sinusoidal measurement of v_T . To regulate the dc-link voltage, vector control of the AFE rectifier would be done considering the WRSG (with AVR control) as weak grid network [16]. Hence the type of interfaced filter plays a significant role in devising control framework for AVR based dc generation system. For instance, v_T while using the L filter is shown in Figure 2(b). The inclusion of the high inductance L will limit the maximum dc voltage at the AFE converter output, slowing down the dynamic response of the system [17]. Thus, LCL filters might be an alternative choice to the L filter [17]–[19]. LC filter can be installed at the generator terminal where X_s along with external LC would thus act as LCL filter.

Such interfaced filters for the applicability in AVR based dc generation system increases the space and weight along with increased cooling requirements at higher loads. Moreover, during the variable speed operation, the voltage reference set-point to the AVR must be changed continuously to regulate terminal voltage/frequency (v_T/f) ratio hence maintaining the

flux of the WRSG.

C. Automatic Flux Regulation based DC Generation System

To avoid interfacing of the filter for the integration of AVR, this paper proposes flux regulation based field excitation system of WRSG and is termed as Automatic Flux Regulator (AFR). Instead of regulating the terminal voltage, AFR directly regulates the machine flux of the WRSG thus indirectly regulating the terminal voltage at the operating speed. Unlike AVR, AFR is independent of the measurement of the WRSG terminal voltage and is an integral part of the flux estimation control routine of the vector control of WRSG [20]. Further, it is independent of the dc bus voltage control at AFE rectifier output which is maintained by controlling torque producing current of the WRSG. This control might be perceived to be derived from the field oriented control of the synchronous machine drive which has received limited attention [20]–[25] due to the dominance of permanent magnet synchronous generator (PMSG) drives [26]–[29] and induction generator drives [30]–[33]. The vector control should be done at the reference frame rotating at synchronous speed to make the control parameters dc quantity [34]. However, it has been reported that the control in the rotor reference frame (RRF) would lead to installation problems such as the requirement of higher voltage rating of WRSG and interfaced AFE rectifier at full load [35]. This has been explained in Subsection III-A. Hence, vector control operation at the stator flux reference frame (SFRF) is selected in this paper which proves to be advantageous as the torque and flux producing current components are decoupled from each other. Further, there is no need of detailed flux equations in M - T axis of SFRF as the aim is to maintain the total flux of the WRSG using the AFR.

D. Research Gaps and Contributions

As detailed before, AVR based field excitation system directly regulates the WRSG terminal voltage while indirectly controlling the WRSG flux. On the contrary, AFR based field excitation system directly regulates the WRSG flux thus indirectly controlling the WRSG terminal voltage. In spite of the advances in the control paradigm of the AFE rectifier; there has been no study to best of the authors' knowledge on the design, control and subsequent comparison of these two field excitation control methods intended for the dc generation system for the application in the emerging marine vessels. Thus the following contributions have been reported in this paper:

- 1) Vector control of AFE rectifier has been devised considering AVR controlled WRSG as weak grid. The AVR operation is supported by filter designed at the desired cut-off frequency. Type-ST based AVR [15] has been chosen for its lower footprint and is expected to be suitable for the marine applications where space and weight reduction is prime concern [6]. This has been included in Section II.

- 2) Vector control of WRSG drive has been devised with the AFR based field excitation system. The control system of AFR based field excitation system is developed by detailed small signal analysis of the variation of the WRSG flux. The derivation of AFR is done analogously with the AVR based field excitation system for easier and fair comparison. This has been reported in Section III.
- 3) Control loop design of AVR and AFR based field excitation system of WRSG for dc generation has been made compliant with IEEE Std. 421.2 [15]. Subsequently, the comparative analysis based on time and frequency domain analysis has been performed and described in Section IV.
- 4) Operation of AVR and AFR based dc generation system for various marine operating conditions have been compared and reported in Section V. The operation such as load change, step change, fault conditions have been validated with hardware-in-loop (HIL) environment.

Discussions on the findings are reported in Section VI and the paper is concluded in Section VII.

II. AVR BASED DC GENERATION SYSTEM

A. Selection of AVR

In comparison with the Fig. 1, the basic blocks (a, b and c) have been considered for the AVR control. The control loop schematic of the Type-ST based AVR for regulation of v_T is shown in Fig. 3. The parameters of the WRSG is indicated in Appendix A. Type-I generator transfer function [13], [36] is considered as shown in Fig. 3 where τ'_{do} is calculated from (1) which comes to be 3.75 s [13].

$$\tau'_{do} = \frac{1}{R'_f} \frac{X_{md} + X_{lf}}{\omega_b}. \quad (1)$$

First order transfer function has been considered for the exciter with $\tau_{exc} = 0.01$ s and $K_{exc} = 1$. The AVR is designed for the bandwidth of 5 Hz as per IEEE Std 421.2 [15]. $G_{AVR}(s)$ is the controller of the AVR which is used to regulate the terminal voltage v_T of WRSG to the desired setpoint v_T^{SP} . The detailed analysis to determine the $G_{AVR}(s)$ is done in Section IV.

Fig. 3. Control system diagram of the Type-ST based AVR for WRSG terminal voltage control.

B. Filter Design for AVR based Field Excitation System

Passive damping with damping resistor R_d has been considered in this paper to mitigate the potential resonant problems. The general schematic of v_T control using AVR with the LC

Fig. 4. (a) Schematic of LC filter interfaced with machine and (b) single phase representation of LC filter.

filter is shown in Fig. 4(a). The single phase diagram of the LC filter is shown in Fig. 4(b), where $E_T(s)$ is the internal voltage of the WRSG, $V_T(s)$ is the terminal voltage and $V_{conv}(s)$ is the converter input voltage which is the source of the switching voltages. The transfer function $F_r(s)$ to determine $V_T(s)$ is illustrated in (2) where filter elements are consistent with the annotations of Fig. 4 and the filter inductor winding resistance (R_f) is neglected.

$$F_r(s) = \frac{V_T(s)}{V_{conv}(s)} = \frac{1/L_f C_f + s R_d / L_f}{s^2 + s R_d / L_f + 1/L_f C_f}. \quad (2)$$

The filter parameters are computed by considering (3) [17]–[19] and is shown in Table I:

$$L_f = \frac{V_{dc} D (1 - D)}{f_{sw} \delta I_p}, \quad C_f = \frac{1}{4\pi^2 f_c^2 L_f}, \quad R_d = 2\zeta \sqrt{\frac{L_f}{C_f}}, \quad (3)$$

where, D is the duty cycle, L_f is chosen as per the allowable ripple content of the generator output current (δI_p), C_f is chosen based on the desired cut-off frequency (f_c) and R_d value is chosen for the given damping ratio (ζ). The cut-off frequency (f_c) should be in the range depicted by the equation stated in (4) [18]:

$$10 f_L < f_c < \frac{f_{sw}}{2}, \quad (4)$$

where, f_L is the line frequency (60 Hz) and f_{sw} is the switching frequency of the converter (5000 Hz). The bode plot of $F_r(s)$ with various damping ratio is shown in Fig. 5(a). Waveform of v_T corresponding to parameters of Table I is shown in Fig. 5(b).

C. System Description and Controller Design

The schematic of the AVR based dc generation system is shown in Fig. 6. The sinusoidal generator terminal voltage

TABLE I
PARAMETERS OF THE LC FILTER

f_c (Hz)	L_f (H)	C_f (F)	R_d (Ω)	ζ	D
1000	3.1×10^{-4}	1.58×10^{-4}	1.9526	0.7	0.5

Fig. 5. (a) Bode plot of LC filter for various damping ratios and (b) terminal voltage of WRSG after interfacing LC filter (v_{Ta} : Red, v_{Tb} : Blue, v_{Tc} : Green).

(v_{Ta} , v_{Tb} , v_{Tc}) at the WRSG terminal is obtained by employing LC filter and is maintained at desired set-point by the AVR. The two-level voltage source converter (2L-VSC) is the AFE converter which perceives this source as weak grid and controls the dc bus voltage and line current by vector control operation [16]. The control is carried out at the reference frame dictated by the PLL. The reference angle for control (θ_p) is computed by the PLL installed at the generator terminals. At this PLL reference frame the v_{ds}^p and v_{qs}^p are decoupled from each other. The currents at PLL reference frame i_{ds}^p controls the active power while the i_{qs}^p controls the reactive power output provided the i_{ds}^p is aligned with the v_{ds}^p . The i_{qs}^p is set to zero to enable unity power factor operation. The phasor representation of such operation is shown in Fig. 7. By this method, operation of the AVR to maintain the WRSG flux/voltage and AFE rectifier operation to maintain dc-link voltage becomes independent of each other. The switching frequency of the converter is set at 5000 Hz, the bandwidth of current control loop is set at 1000 Hz, voltage control loop is set at 100 Hz and the bandwidth of AVR control is set at 5 Hz [15]. The voltage and current control loop is described below.

1) *Voltage Control Loop*: By neglecting the power losses across the filter in Fig. 6, it is assumed that the power generated at Point-A equals to the power output of the converter (Point-B). This can be illustrated by:

$$\frac{3}{2}(v_{ds}^p i_{ds}^p + v_{qs}^p i_{qs}^p) = C \frac{dv_{dc}}{dt} v_{dc} + v_{dc} i_o, \quad (5)$$

Fig. 6. Overview of the functional block diagram of AVR based dc Generation System.

Fig. 7. Phasor diagram for vector control of AFE rectifier interfaced with the WRSG regulated by the AVR at PLL reference frame.

where, v_d^p , v_q^p and i_d^p , i_q^p are calculated at point-A of Fig. 6. As per the proposed control technique at PLL reference frame, $v_q^p = 0$ and $i_d^p = 0$ (for unity power factor). Thus, by applying small signal analysis in (5), the plant transfer function for the voltage control loop ($G_{va}^p(s)$) is derived as shown in:

$$G_{va}^p(s) = \frac{3}{2} \frac{V_{ds}^p}{sCV_{dc} + I_o}. \quad (6)$$

2) **Current Control Loop:** The line currents i_a, i_b, i_c flows from point A to point B through the filter inductor with inductance L_f and inductor winding resistance R_f . The voltage at the converter input terminal is maintained to get the required current flow. The plant transfer function for current loop ($G_{ca}^p(s)$) is shown:

$$G_{ca}^p(s) = \frac{1}{R_f + sL_f}. \quad (7)$$

III. AFR BASED DC GENERATION SYSTEM

A. Selection of Reference Frame

Selection of the reference frame is important to implement the AFR based dc generation system. The reference frame should be synchronously rotating to make the control parameters dc quantities thus enabling easier controllability. As a result RRF or SFRF might be the feasible reference frames. At RRF, the torque (T) is given by:

$$T = 3p \frac{i_{qs}^r \lambda_{ds}^r - i_{ds}^r \lambda_{qs}^r}{4}. \quad (8)$$

The flux equation along d- and q- axis of RRF is given by:

$$\lambda_{ds}^r = -L_{ls} i_{ds}^r + L_{md} (-i_{ds}^r + i_{fd}^r + i_{kd}^r), \quad (9)$$

$$\lambda_{qs}^r = -L_{ls} i_{qs}^r + L_{mq} (-i_{qs}^r + i_{kq1}^r + i_{kq2}^r). \quad (10)$$

By neglecting the damper winding currents ($i_{kd}^r, i_{kq1}^r, i_{kq2}^r$) and setting $i_{ds}^r = 0$, the d-axis flux can be regulated by the field current, i_{fd}^r while the torque can be controlled by varying i_{qs}^r . In such a case, the torque equation becomes:

$$T = 3p \frac{i_{qs}^r \lambda_{ds}^r}{4} = 3p \frac{i_{qs}^r L_{md} i_{fd}^r}{4}. \quad (11)$$

Although the d-axis flux and q- axis current could be controlled independently, the flux along d and q axes are not decoupled completely. This is because, the d-axis flux is controlled by the field current while the q-axis flux is dependent on the q-axis current, which is illustrated below:

$$\lambda_{ds}^r = L_{md} i_{fd}^r, \quad (12)$$

$$\lambda_{qs}^r = L_{mq} i_{qs}^r. \quad (13)$$

The control strategy at RRF, i_{fd}^r will try to keep the λ_{ds}^r constant. However, an increase in load will increase i_{qs}^r which will further increase λ_{qs}^r as per (13). Thus, the total machine flux, $\lambda_s = \sqrt{\lambda_{ds}^r^2 + \lambda_{qs}^r^2}$, also increases with increase in load. This will result in increased operating flux and terminal voltage at higher loads thus requiring higher ratings of the interfaced AFE rectifier [35].

It is thus inferred that selection of reference frame is crucial to implement the AFR based dc generation system. The flux is required to be decoupled at all operating scenarios and should preferably be controlled by the field exciter circuit. On the other hand, the torque output of WRSG could be controlled by the vector control operation of the AFE rectifier. This operation is possible if the control is done at SFRF. The phasor diagram representing the various reference frames of WRSG is shown in Fig. 8. The torque equation of WRSG when the vector control

is carried out at SFRF is shown as [37]:

$$T = 3p \frac{i_{Ts} \lambda_{Ms} - i_{Ms} \lambda_{Ts}}{4}. \quad (14)$$

B. System Description of the Vector Control of WRSG

The proposed AFR based dc generation system is illustrated in Fig. 9 where by theory, $\lambda_{Ts} = 0$ and $\lambda_{Ms} = |\lambda_s|$ (WRSG flux) when the control is done at SFRF ($M-T$ axis). Further, the WRSG is operated at unity power factor by setting $i_{Ms} = 0$. Thus, with the mentioned objectives, the torque equation reduces to:

$$T = 3p \frac{i_{Ts} \lambda_{Ms}}{4}. \quad (15)$$

The output power or equivalently the output dc bus voltage is maintained by varying i_{Ts} according to varying load demand. λ_{Ms} or equivalently λ_s of WRSG is independently controlled by AFR based field excitation. The whole control framework can be divided into five major control blocks, as shown in Fig. 9, and are discussed below:

- B1. Estimation of the phase voltages (v_{abc}) of WRSG is done by the dc-link voltage and the switching combination (S_{abc}) of the AFE rectifier [8].
- B2. After v_{abc} is estimated, the angle to convert the control parameters into SFRF is computed. This angle (θ_s) is calculated by $\tan^{-1}(\lambda_\beta / \sqrt{\lambda_\alpha^2 + \lambda_\beta^2})$ where λ_α and λ_β are flux components in the α and β axes which are in stator reference frame (Fig. 8).
- B3. The flux linkages per second in $M-T$ axis (SFRF) i.e. ψ_{Ms} and ψ_{Ts} are estimated utilizing θ_s computed in Step B2. By theory, $\psi_{Ts} = 0$, and the ψ_{Ms} ($= \psi_s$, WRSG flux linkages per second) is fed to the AFR based excitation control.
- B4. The AFR based excitation control maintains ψ_{Ms} or (equivalently λ_s) to specified set-point defined by the user. This is maintained by varying the field current and field voltage in accordance to changing load angle (δ).
- B5. The power control loop consists of voltage and current control loop. The design of these loops and the selected

Fig. 8. Phasor diagram showing the relative orientation of $d-q$ and $M-T$ axes for WRSG.

bandwidth are similar to the design presented in Section II-C respectively with the only difference is that the present control is done in $M-T$ axis. This loop is independent of the flux control by AFR in Step B4. The voltage loop (G_{vf}) is computed from the small signal analysis of the power balance equation in (16) and is illustrated in (17). The current loop transfer function is also shown in (17).

$$3p \frac{i_{Ts} \lambda_{Ms}}{4} \omega_r = C \frac{dv_{dc}}{dt} v_{dc} + v_{dc} i_o. \quad (16)$$

$$G_{vf}(s) = \frac{3}{4} \frac{p \lambda_{Ms} \omega_r}{s C V_{dc} + I_o}; \quad G_{cf}(s) = \frac{1}{R_s + s L_s}. \quad (17)$$

C. Control Loop Derivation of AFR Based WRSG Field Excitation System

One of the objective of AFR is to control the stator flux (λ_s) by field excitation circuit which can equivalently be achieved by regulating the stator flux linkage per second, $\psi_s (= \psi_{Ms})$ to the desired value. The voltage equation of WRSG equations in terms of flux linkages/second in $M-T$ frame is illustrated in (18a) and (18b) [37].

$$v_{Ms} = -r_s i_{Ms} - \frac{\omega_r}{\omega_b} \psi_{Ts} + \frac{1}{\omega_b} \frac{d}{dt} \psi_{Ms}, \quad (18a)$$

$$v_{Ts} = -r_s i_{Ts} + \frac{\omega_r}{\omega_b} \psi_{Ms} + \frac{1}{\omega_b} \frac{d}{dt} \psi_{Ts}, \quad (18b)$$

and the WRSG terminal voltage v_t is given by (18c),

$$v_t^2 = v_{Ms}^2 + v_{Ts}^2, \quad (18c)$$

Fig. 9. Overview of the vector control of WRSG drive for dc bus voltage control and AFR for WRSG control.

where, v_{Ms} & v_{Ts} are phase voltages, i_{Ms} & i_{Ts} are line currents, ψ_{Ms} & ψ_{Ts} are flux linkages per second in M - T axis. r_s is WRSG stator resistance, ω_b and ω_r are base speed and generator speed respectively. As $\psi_{Ms} = \text{constant}$ and $\psi_{Ts} = 0$ in M - T axis; by neglecting r_s , the equation of terminal voltage becomes:

$$v_t^2 = v_{Ms}^2 + v_{Ts}^2, \quad (19a)$$

$$v_t^2 = \left(\frac{1}{\omega_b} \frac{d}{dt} \psi_{Ms} \right)^2 + \left(\frac{\omega_r}{\omega_b} \psi_{Ms} \right)^2 \quad (19b)$$

where, $\psi_{Ms} = \psi_s$. Thus by applying small signal analysis on (19b), the relation between ψ_{Ms} and v_t can be found out.

$$(V_t + \hat{v}_t)^2 = \left(\frac{1}{\omega_b} \frac{d}{dt} (\Psi_{Ms} + \hat{\psi}_{Ms}) \right)^2 + \left(\frac{\omega_r}{\omega_b} (\Psi_{Ms} + \hat{\psi}_{Ms}) \right)^2 \quad (20a)$$

$$\frac{d}{dt} (\Psi_{Ms} + \hat{\psi}_{Ms}) = \omega_b (V_t + \hat{v}_t) \sqrt{1 - \left(\frac{\omega_r (\Psi_{Ms} + \hat{\psi}_{Ms})}{\omega_b (V_t + \hat{v}_t)} \right)^2} \quad (20b)$$

The RHS of the (20b) is of the form $A_k(1-x)^{1/2}$ which can be expanded binomially and linearised by neglecting higher order terms to get (20c),

$$\frac{d}{dt} (\Psi_{Ms} + \hat{\psi}_{Ms}) \approx \omega_b (V_t + \hat{v}_t) \left(1 - \frac{1}{2} \left(\frac{\omega_r (\Psi_{Ms} + \hat{\psi}_{Ms})}{\omega_b (V_t + \hat{v}_t)} \right)^2 \right) \quad (20c)$$

$$\frac{d}{dt} \hat{\psi}_{Ms} \approx 2\omega_b \hat{v}_t - \frac{\omega_r^2}{\omega_b} \frac{\Psi_{Ms}}{V_t} \hat{\psi}_{Ms}. \quad (21a)$$

Applying Laplace transform

$$s\hat{\psi}_{Ms}(s) \approx 2\omega_b \hat{v}_t(s) - \frac{\omega_r^2}{\omega_b} \frac{\Psi_{Ms}}{V_t} \hat{\psi}_{Ms}(s). \quad (21b)$$

Re-arranging the terms we will get the relation between $\hat{\psi}_{Ms}(s)$ ($= \hat{\psi}_s(s)$) and $\hat{v}_t(s)$ as shown in (21c).

$$\frac{\hat{\psi}_s(s)}{\hat{v}_t(s)} \approx \frac{\omega_b}{\frac{1}{2}s + \frac{1}{2} \frac{\omega_r^2}{\omega_b} \frac{\Psi_s}{V_t}}. \quad (21c)$$

This relation between $\hat{\psi}_s(s)$ and $\hat{v}_t(s)$ will be used to determine the plant transfer function and to design the controller of the AFR based field excitation system. The AFR based controller is implemented as shown in B4 block of Fig. 9. The schematic for the AFR based WRSG control is depicted in Fig. 10 where the Ψ_s is maintained at the desired setpoint Ψ_s^{SP} dependent on the $G_{AFR}(s)$. $G_{AFR}(s)$ is determined by the plant transfer function of generator, exciter and $D(s)$ as analyzed in Section IV.

IV. CONTROLLER RESPONSE ANALYSIS

In the dc generation system, the aim of both AVR and AFR based field excitation system is to regulate the operating flux of the WRSG within the prescribed operating limits. AVR does this by maintaining the terminal voltage of WRSG

Fig. 10. Functional block diagram of the field excitation circuit in the proposed AFR based control.

against speed dependent setpoint whereas the AFR does this by regulating the WRSG flux to its rated value which is described in Section II and Section III respectively. In this section, comparative analysis of the AFR with AVR based field excitation is carried out to support its effectiveness and highlight its potential benefits.

A. Controller Design and Frequency Response Analysis

One of the prime difference between the control structure of the AVR and AFR based excitation system is the need of additional transfer function $D(s)$ (in (22)) in the AFR based system as marked in Fig. 10.

$$D(s) = \frac{\omega_b}{\frac{1}{2}s + \frac{1}{2} \frac{\omega_r^2}{\omega_b} \frac{\Psi_s}{V_t}} \quad (22)$$

$G_{AVR}(s)$ and $G_{AFR}(s)$ shown in Fig. 3 and 10 are the controllers of the AVR and AFR which are used to maintain the terminal voltage and machine flux respectively at defined setpoints and within the required bandwidth. As per, IEEE Std 421.2, bandwidth of 5 Hz is chosen for the field regulating applications. Conventionally, $G_{AVR}(s)$ and $G_{AFR}(s)$ are modeled by proportional controllers (P-controllers) to maintain the desired bandwidth, which will have persistent steady-state errors. Thus, in addition to the P-controller, this paper also considers K-factor based controller which is based on the pole-zero placement technique [38]. In this way, steady-state and transient responses could be studied when the type of controllers are altered. The general structure of the P-controller is:

$$G_{AVRP}(s) = \frac{K_P}{1 + s\tau_P}, \quad (23)$$

where, K_P is the gain and τ_P is the time-constant of the amplifier. Generally, τ_P is very small constant value while K_P is adjusted to get the desired bandwidth. On the other hand, the general structure for the K-factor based controller is:

$$G_{AVRK}(s) = \frac{K_K}{s} \left(\frac{1 + s/\omega_z}{1 + s/\omega_p} \right). \quad (24)$$

In such controllers the gain K_K , pole ω_p and zero ω_z could be adjusted to obtain the desired bandwidth and phase margin. For a fair comparison, bandwidth of both AVR and AFR have been fixed at 5 Hz. The controller transfer functions for AVR and AFR are shown in Table II. Bode plot of both systems are compared in Fig. 11. It can be observed that the responses of both AVR and AFR are similar in the low frequency region.

TABLE II
CONTROLLER TRANSFER FUNCTIONS FOR AVR AND AFR SYSTEM

Control	AVR ($G_{AVR}(s)$)	AFR ($G_{AFR}(s)$)
Proportional Control	$\frac{124}{1 + 0.001s}$	$\frac{63}{1 + 0.001s}$
K-factor Control	$\frac{77.18}{s} \left(\frac{1 + s/31.42}{1 + s/161.97} \right)$	$\frac{28.38}{s} \left(\frac{1 + s/0.45}{1 + s/217.96} \right)$

Due to the presence of $D(s)$, the gain and phase margin of AFR are lesser than AVR but within permissible limits. The frequency-domain metrics for such normal operating conditions are presented in Table III.

Fig. 11. Comparison of the bode plot of AVR and AFR based excitation system for (a) P-control and (b) K-factor based control.

B. Step Response Analysis

Fig. 12 compares the step response of the closed-loop voltage control for AVR and closed-loop flux control for AFR based field excitation system. As the bandwidth of both systems is kept same, the rise times are reasonably comparable. Although other parameters such as peak amplitude of AFR is different from AVR but are within permissible limits as prescribed by IEEE Std 421.2 [15]. The time-domain metrics for such normal operation are depicted in Table III.

Fig. 12. Comparison of the step response of (a) AVR and (b) AFR based field excitation system using both P-control and K-factor based control.

C. Response to Change in Parameters and Operating Limits

The controllers $G_{AVR}(s)$ and $G_{AFR}(s)$ are designed considering the plant transfer functions of exciter and WRSG.

Inaccurate determination of the plant transfer functions might adversely effect the field regulating operation. To test the robustness and operating capabilities of the AVR and AFR based field excitation system, the system parameters such as K_{exc} and τ_{exc} of the exciter and τ'_{do} of WRSG are varied [39]. Time-domain, frequency-domain and stability performance metrics are monitored which are shown in Table III. It is observed that the AFR based system offers similar characteristics than the AVR based system.

V. OPERATIONAL ANALYSIS

With reference to the modeling and control framework developed in Section II, III and IV; this section presents the operation of both AVR and AFR based dc generation system. This operation has been validated with the Opal-RT OP5600 based HIL real-time simulation platform [2], [40], [41]. The marine loads and contingencies have been tested for both types of generation systems for detailed one-to-one comparison.

A. Output with Step Change in Set-point of Control Parameter

Step change in the terminal voltage (for AVR) and flux set-points (for AFR) are changed from 1.0 pu to 1.1 pu at 4 s and to 0.9 pu at 8 s to study its impact on the field current requirements and output dc bus voltage. The results are shown in Fig. 13 and 14 respectively. Both P-control and K-factor based controller are implemented and compared. As expected, it is seen that there is a persistent steady-state error for proportional control while the control variable closely follows the set-point for the K-factor based method. It can further be seen that the dc bus voltage is more sensitive to the step change in AVR control. The overshoot in the dc bus voltage for AVR is 1.17% while with AFR is 0.73%. In both cases the overshoot is within permissible limits according to the IEEE Std 421.2 [15].

B. Decoupling of the Control Parameters

For the AFR based control, ψ_{Ms} (or equivalently λ_{Ms}) should be decoupled from ψ_{Ts} (or λ_{Ts}). Similarly, decoupling of v_{ds}^p from v_{qs}^p is required for the AVR based control. For unity power factor i_M (in AFR) and i_q^p (in AVR) is maintained at zero. The control parameters must be de-coupled at all load condition and also during the load change transients. This is shown by the load change operation as shown in Fig. 15. The generator output is varied from 1300 kW to 1850 kW at 5 s and again restored to 1300 kW at 8 s. Fig. 15(a) and 15(b) shows the decoupled control parameters during this operation. The K-factor based control is used for both AVR and AFR based dc generation system.

C. Verifying the Stability Limits

The stability limits of both the AVR and AFR operating with P-control are primarily dominated by the selection of gains

TABLE III
PERFORMANCE METRICS OF AVR AND AFR BASED FIELD EXCITATION SYSTEM TO VARYING SYSTEM PARAMETERS

Conditions	Parameters		AVR Based System		AFR Based System	
			P-Control	K-Factor	P-Control	K-Factor
Normal Operating Conditions	Time Domain Parameters	Rise Time (s)	0.0455	0.0385	0.0403	0.0372
		Settling Time (s)	0.0718	0.1271	0.1054	0.1233
		Overshoot (%)	0.7973	7.5146	2.99	8.45
		Undershoot (%)	0	0	0	0
	Frequency-Domain Parameters	Gain Margin (dB)	33.3637	7.7131	9.91	5.58
		Phase Margin (deg)	71.1844	60.7919	66.17	59.26
		Bandwidth (Hz)	5.01	5.03	5.06	5.00
	Stability Limits	Gain (K)	4137	595	624	158
50% Increase in both Exciter Time Constant and Gain	Time Domain Parameters	Rise Time (s)	0.0443	0.0395	0.0281	0.0284
		Settling Time (s)	0.1284	0.1403	0.1492	0.1524
		Overshoot (%)	5.174	13.936	18.99	18.48
		Undershoot (%)	0	0.77	3.63	3.61
	Frequency-Domain Parameters	Gain Margin (dB)	32.39	6.72	6.25	6.26
		Phase Margin (deg)	64.46	54.37	49.21	49.21
		Bandwidth (Hz)	4.79	4.81	6.72	6.69
	Stability Limits	Gain (K)	4017	571	393	118
50% Reduction of both Exciter Time Constant and Gain	Time Domain Parameters	Rise Time (s)	0.0527	0.0407	0.1093	0.1152
		Settling Time (s)	0.0962	0.0652	0.2018	0.2018
		Overshoot (%)	0	1.6129	0	0
		Undershoot (%)	0	0	0	0
	Frequency-Domain Parameters	Gain Margin (dB)	36.35	10.6746	22.91	23
		Phase Margin (deg)	79.34	68.71	82.65	82.35
		Bandwidth (Hz)	5.19	5.2	2.65	2.64
	Stability Limits	Gain (K)	4507	647	1443	240
50% Increase in τ'_{do}	Time Domain Parameters	Rise Time (s)	0.0754	0.0611	0.0676	0.0691
		Settling Time (s)	0.1339	0.1892	0.1178	0.1232
		Overshoot (%)	0	2.2518	0	0
		Undershoot (%)	0	0	0	0
	Frequency-Domain Parameters	Gain Margin (dB)	49.99	11.55	14.85	14.90
		Phase Margin (deg)	77.08	68.89	73.61	73.43
		Bandwidth (Hz)	3.42	3.47	3.47	3.45
	Stability Limits	Gain (K)	6200	894	935	239
50% Reduction in τ'_{do}	Time Domain Parameters	Rise Time (s)	0.0221	0.021	0.0203	0.0205
		Settling Time (s)	0.0734	0.1552	0.109	0.1128
		Overshoot (%)	11.05	27.74	19.83	18.92
		Undershoot (%)	1.2	8.1	4.72	4.7
	Frequency-Domain Parameters	Gain Margin (dB)	16.73	3.87	4.97	4.99
		Phase Margin (deg)	57.44	41.76	48.73	48.76
		Bandwidth (Hz)	9.1	8.87	9.1	9.1
	Stability Limits	Gain (K)	2074	296	313	78

Fig. 13. (a) WRS terminal voltage, (b) WRS field current and (c) dc-link voltage for P-control and K-factor based $G_{AVR}(s)$ with step change in WRS terminal voltage setpoint.

Fig. 14. (a) WRSg flux, (b) WRSg field current and (c) dc-link voltage for P-control and K-factor based $G_{AVR}(s)$ with step change in WRSg flux setpoint.

Fig. 15. (a) Decoupling of v_{ds}^p and v_{qs}^p ; i_{ds}^p and i_{qs}^p for AVR based system and (b) decoupling of λ_{Ms} and λ_{Ts} ; i_{Ms} and i_{Ts} for AFR based system when generator output is altered.

K_{pa} (for AVR) and K_{pf} (for AFR). Analysis of the root locus diagram in Figure 16(a) shows that the gain K_{pa} increasing beyond 4137 leads to instability in the AVR control. This is evident from the study of the corresponding change in field voltage E_{fd} is shown in Figure 16(c). The E_{fd} fluctuates from 0 pu to 6 pu when $K_{pa} > 4137$ making the AVR based control inoperable. Similarly, root locus diagram in Figure 16(b) infers that the gain K_{pf} increasing beyond 624 would lead to instability in the AFR system. This is supported by the corresponding change in field voltage E_{fd} is shown in Figure 16(d). It can be observed that for higher gains ($K_{pf} > 624$), E_{fd} fluctuates from 0.5 pu to 3.5 pu making the AFR based excitation control inoperable.

D. WRSg Loading and Field Current Requirements

Loading of the propulsion system is emulated in Fig. 17(a) where the WRSg is gradually loaded from the no-load to nearly full-load (1850 kW) condition. In this process, it is observed that the field current requirement for the AFR based

Fig. 16. The stability limits of the AVR and AFR based control with the variation of (a) K_{pa} and (b) K_{pf} ; the variation of output field voltage while changing (c) K_{pa} for AVR and (d) K_{pf} for AFR.

dc generation system is less than that of the AVR based dc generation. For AVR based system, the active power and reactive powers are regulated by i_{ds}^p and i_{qs}^p , respectively. On the other hand, active and reactive powers in AFR based system are regulated by i_{Ts} and i_{Ms} , respectively. For similar loading scenarios the variation of i_{ds}^p and i_{qs}^p (for AVR) and i_{Ts} and i_{Ms} (for AFR) are shown in Fig. 17(b). In this paper, i_{qs}^p (for AVR) and i_{Ms} (for AFR) are maintained at zero for unity power factor operation. Conversion of these currents from their respective reference frames (PLL reference frame for AVR and SFRF for AFR) to RRF is done, which is indicated in Fig. 17(b). It is seen that the d-axis current at RRF for AVR based dc generation has higher magnitude than that of the AFR based dc generation system. It is known that the field current requirement depends on the WRSg flux and to counter the d-axis current at RRF [37]. Thus, this requirement is higher for the AVR based dc generation system which has lower field

current as compared to the AFR based dc generation system. This becomes one of the major advantages of using the AFR based dc generation for dc marine vessels.

Fig. 17. (a) Variation of field current for AVR and AFR based dc generation system when WRSG is loaded from no-load to nearly full-load (1850 kW). (b) Current components in SFRF (for AFR based system) and in PLL reference frame (for AVR based system) along with the decomposed components in the RRF.

E. Operation during Variable Speed

The dc marine vessels are expected to integrate the variable speed DGs. During such operation, the operating parameter such as the machine flux of the interfaced WRSG should be maintained at nominal values. For AVR based system, the terminal voltage set-point of WRSG should be altered continuously with the operating speed so that constant v_t/f ratio is maintained and machine flux does not reach the saturation region. On the other hand, in the AFR based WRSG, machine flux is directly regulated at the desired setpoint without the need of any set-point variation as compared to the AVR based system. This is a major advantage of the AFR based generation system. This operation is shown in Fig. 18 when the speed is changed from 1 pu to 0.85 pu at 5 s.

For AFR based system in Fig. 18(a), WRSG flux is maintained at desired setpoint (1.49 Wb) while the field current increases to regulate the flux at lower speed. For the AVR based system the WRSG terminal voltage setpoint is changed according to the WRSG operating speed. With the changing speed, the WRSG terminal voltage setpoint is changed from 1 pu to 0.85 pu as shown in Fig. 18(b) and 18(c). When the setpoint is changed abruptly from 1 pu to 0.85 pu, there is a transient effect in the field current and the machine flux. However, if the voltage setpoint is altered for every operating speed, the transient effect in WRSG field current and flux is minimized.

F. Operation during the Fault Conditions

The fault resistance of 0.01Ω is introduced at the terminal of AFE rectifier for both AFR and AVR based dc generation system when it was delivering 2000 kW power to study the response of the field excitation circuit and the output fault current. For both cases, the field voltage E_{fd} rises to the maximum upper limit (Fig. 19) which set as per IEEE Std 421.2 [4], [15]. The initial fault current due to capacitor

discharge is equal at 12 kA for both cases. The ac fault current delivered by the WRSG in case of AVR based system is limited by the filter inductor, hence it is lower than the AFR based system which can be seen from Fig. 19(b, d).

VI. DISCUSSION

Based on the operation and control of the AVR and AFR based dc generation system, the following discussions are cited:

- 1) Conventionally, the generation system in traditional ac marine vessels is based on AVR based field excitation system, which is dependent on the measurement of the terminal voltage of WRSG. However, in the 2L-VSC based dc generation system, the terminal voltage can only be measured by employing a tuned LC filter, which increases the space and weight requirements and further increases the cost. Contrarily, the proposed AFR based control does not require the measurement of terminal voltage thus not requiring an additional LC filter. This is the principal advantage of the AFR based dc generation system as compared to the AVR one. This reduces the complexity of the control, helps in restricting the size and space requirements and avoids the need of additional cooling requirements for the filter during full load conditions.
- 2) AVR regulates the terminal voltage while AFR maintains the WRSG flux. Thus, the modeling and derivation of the required 'terminal voltage to flux' transfer function and control loop design for the field excitation circuit have been derived for the AFR based dc generation system. This was the prime research gap in the existing literature. This design has been done analogously to the AVR based field excitation system.
- 3) DC-link voltage control for the AVR based dc generation system is carried out by the vector control operation of the interfaced AFE rectifier at PLL reference frame. This is done by considering the WRSG and interfaced LC filter as weak grid network. It serves as the base model and is used for comparison with the AFR based dc generation system. The dc-link voltage control for AFR system is done by vector control operation of the WRSG fed AFE rectifier at SFRF.
- 4) Controller response analysis with the emphasis on the variation of system parameters in both AVR and AFR yields similar results. This makes AFR a suitable alternative to the AVR based dc generation system. The AFR based dc generation system is evidently promising which is supported by the stability analysis and the detailed comparative analysis with AVR based dc generation in both time- and frequency- domain.
- 5) AFR directly regulates the WRSG flux, thus changing the speed of WRSG would not effect the operating parameters. However, AVR requires the v_T^{SP} to be varied in according to the changing speed. It is seen that the abrupt change of v_T^{SP} results in transient variation of the

Fig. 18. (a) WRSg flux and field current when the operating speed of DG is reduced from 1 pu to 0.85 pu at 5 s for AFR based dc generation system. Variation of (b) WRSg flux and (c) field current requirement when operating speed is reduced from 1 pu to 0.85 pu at 5 s for AVR based dc generation system and when terminal voltage setpoint is unchanged, abruptly changed and varied in according to the WRSg speed from 1 pu to 0.85 pu at 5 s.

TABLE IV
AVR VS AFR BASED DC GENERATION SYSTEM

Parameter	AVR based dc Generation System	AFR based dc Generation System
WRSg Excitation Control Parameter	Terminal Voltage (v_T)	Flux Linkage per second (ψ_s) / Flux (λ_s)
Reference Frame for WRSg & AFE converter control	As per PLL	Stator Flux Reference Frame
De-coupling Parameters	i_{ds}^p and i_{qs}^p ; v_{ds}^p and v_{qs}^p	i_{Ms} and i_{Ts} ; ψ_{Ms} and ψ_{Ts}
Additional Requirements	Need of LC filter	Need of converter switching combinations
Footprint	More due to LC filter	Expected to be less
Losses	More for passive damping based LC filter	Expected to be less
Variable Speed Operation	Manual change of voltage set-point	No change of set-point
Voltage Sensors	3 (ac) + 1 (dc)	1 (dc)
Cost	More due to additional voltage sensors, LC filters and cooling requirements	Lesser than AVR due to direct connection of WRSg with VSC resulting in less number of voltage sensors and LC filters

Fig. 19: (a) Field voltage & (b) dc fault current for the AFR based system and (c) field voltage & (d) dc fault current for AVR based system.

WRSg flux and field current. As a result, it is required that v_T^{SP} has to be altered at every operating speed for smoother operation. Thus, additional arrangements are needed to provide the speed dependent v_T^{SP} .

- 6) It is observed that for similar loading condition field current requirement for AFR based dc generation system is more than that of AVR based dc generation system. This is because the AVR based control is done at PLL

reference frame and AFR based control is done at SFRF. When converted into RRF, the d-axis current (in RRF) is higher in the case of the AVR based control. Thus higher field current is needed to counter this d-axis current and also to establish the WRSg flux. Therefore, the AFR based system would require lower rated field circuit as compared to the AVR based system. This becomes an additional advantage of using AFR based dc generation system.

With regards to the discussion, the comparison of both types of dc generation system is illustrated in Table IV.

VII. CONCLUSION

This paper investigates the suitability of automatic flux regulation (AFR) based excitation control of the WRSg for the application in the dc generation system for emerging marine vessels. The efficacy of the proposed method is supplemented by the comparative analysis with the conventional automatic voltage regulation (AVR) based field excitation control. This study would be helpful in the development and selection of the type of field excitation system to control the WRSg for such applications. Detailed modeling for both systems are done which substantiates the suitability of the AFR based dc generation system in the emerging dc marine vessels.

APPENDIX

WRSG Rating : 2048 kVA, 690 V, 60 Hz, 8 pole. **Armature Circuit :** $R_s = 0.002591$ pu, $X_{ls} = 0.007$ pu, $X_d = 1.87$ pu, $X'_d = 0.219$ pu, $X''_d = 0.116$ pu, $X_q = 1.05$ pu, $X'_q = 0.121$ pu. **Field Circuit :** $R_f = 0.002$ pu, $X'_f = 0.5$ pu.

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