

Current Source Converter Based Offshore Wind Farm with Medium Frequency Transformer Using Fuzzy Logic Controller

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ABSTRACT: Offshore wind farms with series structures are promising design of the fact that costly and costly offshore substations can be reduced. In this present work, a medium-frequency transformer (MFT) - based wind energy conversion is proposed for such offshore wind farm based on current source converter. The present arrangement comprises of a medium-voltage permanent magnet synchronous generator that is associated with a minimal effort inactive rectifier, a MFT-based cascaded converter, and a current source inverter. Aside from satisfying conventional control targets, this work attempts to guarantee uniformly conveyed power and voltage sharing among the constituent modules given the fell structure of the MFT-based converter. This paper completely examines the normal for decoupling between the voltage control adjusting of the secluded converter and the other control targets. At long last, both exploratory outcomes are given to mirror the execution of the proposed framework.

KEYWORDS: Current source converter, permanent magnet synchronous generator, wind energy conversion system, medium-frequency transformer, cascaded DC-DC converter.

I.INTRODUCTION

Among all existing renewable energy sources, wind energy (onshore and offshore) has progressively turned into a standard one [1]. Dissimilar to inland applications, introduced offshore wind power capacity is just 2% of the aggregate limit starting at 2012 [2]. In any case, an expanding pattern is gauge as a result of [3] (a) wind assets are significant. (b) Offshore wind speed is frequently fundamentally higher and steadier than that onshore. (c) The ecological impact (capable of being heard clamor and visual impact) is the limited in offshore applications.

On the premise of the association strategies for twist turbines in offshore wind ranches and the qualities of the ability to be conveyed, the wind vitality change framework (WECS) proposed in writing and actualized essentially can be ordered into four sorts [4]–[7]: parallel air conditioning association and high voltage alternating current (HVAC) transmission systems, parallel air conditioning association and high voltage direct current (HVDC) transmission systems, parallel dc association and HVDC transmission systems, and arrangement dc association and HVDC transmission systems. The HVAC framework is reasonable for application where the transmission separate is lower than 50 km, while HVDC framework rules the market when the transmission remove is longer than 50 km. Every one of these arrangements aside from the fourth one require offshore substation which is extremely massive and exorbitant. Besides considering unwavering quality and effectiveness as fundamental imperatives for all coastal change systems, the impressions and weights of the segments are especially critical for offshore foundation. The aggregate weight of the framework that is commanded by the offshore substation altogether influences the cost and multifaceted nature of the offshore wind cultivates. In this manner, the fourth one (arrangement dc association and HVDC transmission framework) is progressively underlined in explore in light of the fact that it can spare altogether cost given that the cumbersome and expensive offshore substation can be disposed of [8].

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MV-based power converters, which are pivotal parts in WECS, can be classified into voltage source converters (VSCs) and current source converters (CSCs). From one viewpoint, VSC-based WECS overwhelms offshore wind farm applications.

In the present work, a medium frequency transformer (MFT) - based WECS is proposed for arrangement associated CSC-based offshore wind ranches (Fig. 1). The setup comprises of a MV PMSG that is associated with a minimal effort three-stage diode rectifier, a particular MFT-based converter, and an inland CSI associated with the lattice through a multi-winding transformer. The present paper for the most part concentrates on two of the real issues in a offshore wind farm. One is to dispose of the cumbersome and expensive offshore substation, and the other is to take out the massive and overwhelming low-frequency transformer which is regularly introduced in the nacelle or inside the tower of the wind turbine.

II. CONFIGURATION OF THE PROPOSED WECS

Fig. 1 demonstrates the general structure of the CSC-based offshore wind cultivate. N quantities of the proposed MV PMSG-based WECSs are associated in arrangement with one basic dc-connect inductor L_{dc} . The coastal CSIs are associated with the matrix through multi-winding transformers. Fig. 2 delineates the topology of the proposed MFT-based WECS; the design comprises of a MV PMSG, a three-stage diode rectifier, a secluded MFT-based converter, and a CSI that is associated with the network through a transformer. C_f is the output capacitor and L_g speaks to the framework side inductance. Fig. 3 represents the definite topology for the particular MFT-based converter, in which N quantities of voltage-bolstered, current-output converters (without a output capacitor channel) are associated in arrangement, at that point specifically associated with the dc-interface inductor L_{dc} . CN ($N = 1, 2 \dots, N$) is input capacitor of every module in the fell converter.

The front-end converter, and the latent rectifier shows the upsides of unwavering quality, ease, being little and light, and having a more straightforward generator-side control than a PWM converter dosage. Moreover, the synchronous inductance of a PMSG is for the most part over 0.4 for every unit (pu) for high-control, low-speed wind applications, which further helps to mitigate the torque ripple.

low-frequency three-stage transformer is utilized, the proposed secluded MFTs-based arrangement is focal points in terms of higher power thickness, little impression and weight (which is significantly more vital for offshore application). In expansion, by the proposed

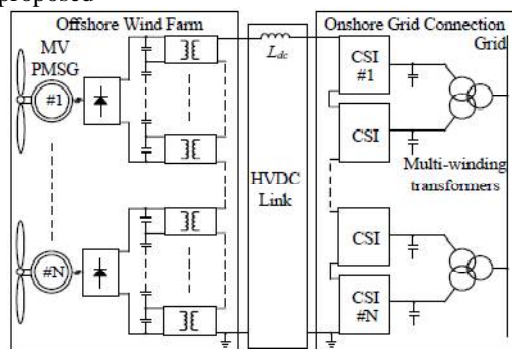


Fig. 1. Proposed configuration of CSC-based offshore wind farm

MFT-based converter, as it were optional side segments of MFTs (diodes rectifier) are required for high voltage protection, while both offshore converters and capacitors are required in. As appeared in Fig. 1, every one of the parts are comparatively evaluated, however the protection levels are not uniform. The protection necessity is decreased at the point when the wind turbine unit is situated close to the ground point. A planned control plot was proposed for a

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arrangement associated CSC-based offshore wind cultivate in a past think about. By differentiate, the present work concentrates on the control plan of the single MV PMSG-based WECS (Fig. 2).

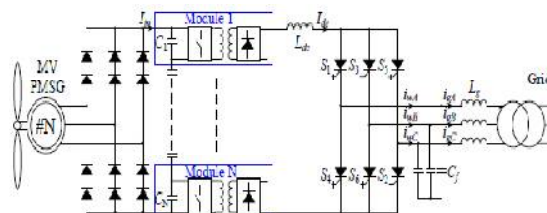


Fig. 2. Proposed MFT-based WECS.

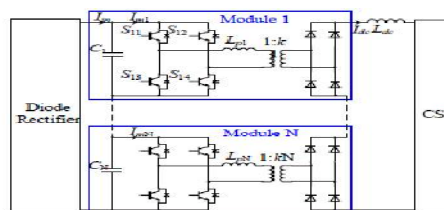


Fig. 3. Modular DC-DC converter

III. ANALYSIS OF THE MODULAR CONVERTER

The particular converter (Fig. 3) assumes essential parts in the proposed WECS. To begin with, it is helpful for accomplishing both MPPT and, lattice side control. Second, MFT is utilized on the grounds that of the generator protection issue which has been examined in the past area, along these lines not rehased here. Rather than utilizing cumbersome low-frequency transformers, MFTs are utilized given their points of interest of high power thickness and simple offshore development. Expanding working frequency brings about a huge decrease in size and weight of the transformer. In any case, in the application MV Megawatts-level WECS, a few difficulties ought to be considered: (a) Losses and warm plan. A critical test will be acquainted with warm what's more, cooling framework outline because of the blend of little size furthermore, high misfortunes as expanding operation frequency; (b) challenge originating from the protection outline of high-control MFT. In uses of arrangement associated wind cultivate, the greatest potential the transformer must withstand is the full transmission level.

A. Determination of the number of cells

The base required number of cells for the proposed arrangement relies upon: (a) input dc voltage, (b) the voltage rating of the chosen protected entryway bipolar transistor (IGBT), what's more, (c) the picked cell voltage. The appraised input dc voltage is roughly 5000 V for a 4000 V PMSG-based framework. 1700 V IGBT is chosen since it is the most appropriate exchanging gadget regarding cost, voltage use, and disappointment in time rate for MV applications. Given a cell voltage of 1000 V, five cells (without excess) must be associated in arrangement at both the info and the output. A converter with six cells can likewise be decided for repetition (N+1); in any case, this work considers a measured converter with five cells.

B. MFT

The topology of every module that is utilized in the MFT-based converter (Fig. 3) is a voltage-bolstered, current-output, full-connect converter with a typical inductor (L_{dc}) channel. In this investigation, the MFT assumes two parts: First, this transformer can help acknowledge zero-voltage exchanging for the essential switches through spillage inductance L_{pN} ($N = 1, 2, \dots, 5$) without requiring extra parts. Second, MFT performs a detachment work. As said in the past area, the MFT must withstand a full transmission voltage at most; subsequently the issue of MFT protection must be considered in useful outline and produce.

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A. Operation Principle

One preferred standpoint of a secluded converter is its control conspire can be streamlined that every single constituent module share the same control. It implies the drive signals for S11, S21 ... S51 are same (Fig. 3) as are different switches. Here, we take Module 1 as an case to represent the operation rule. The ordinary stage moved tweak conspire is utilized where all the switches work with settled half obligation cycle, while the period of the second leg is moved to exchange the power. The consistent state waveform is appeared in Fig. 4 where the dead time between switches in a similar leg is not appeared. S11, S12, S13, and S14 are the comparing drive signals; I_{dc} and i_{p1} are dc-link current also, transformer essential currents (Fig. 3), separately; V_{o1} is the output voltage. The comparing operation states are appeared in Fig. 5. Before t_0 , switches S11 and S14 are on, thus are D11 and D14 (Fig. 5 [a]). The transformer essential/optional streams i_{p1}/i_{s1} and the output voltage V_{o1} are currently kept at 1 pu, also, the power is exchanged to the heap. $t_0 < t < t_1$: At time t_0 , S14 is off, essential current i_{p1} commutates from S14 to the parallel diode of S12 amid the dead time; in this way, S12 is turn on with zero voltage exchanging (ZVS). Amid this period, streams i_{p1}/i_{s1} are somewhat diminishing to under 1 pu, while the dc-connect current I_{dc} is controlled to keep up at 1 pu by the CSI; accordingly, D12 and D13 are turn on (D11 and D14 are remaining on). The output voltage V_{o1} is presently remaining at 0 pu, and no power is exchanged (Fig. 5 [b]). $t_1 < t < t_2$: At time t_1 , S11 is off, and as same as that in the past period, S13 is turn on with ZVS. Streams i_{p1}/i_{s1} is currently diminishing forcefully with the incline dictated by the information voltage and the estimation of the spillage inductor. Amid this period, D11, D12, D13 and D14 are as yet kept on and no power is exchanged (Fig. 5 [c]). $t_2 < t < t_3$: At time t_2 , Streams i_{p1}/i_{s1} is diminishing to -1 pu; in the interim, D11 and D14 are off, while D12 and D13 are continued. The output voltage V_{o1} is currently remaining at 1 pu, and the power is exchanged to the stack (Fig. 5 [d]). $t_3 < t < t_4$: At time t_3 , S12 is off; S14 is turn on with zero voltage exchanging (ZVS). The operation standard is same as that amid $t_0 < t < t_1$. In this way is not rehashed here (Fig. 5 [e]). After t_4 , same operation cycle rehashes as appeared in Fig. 4.

IV. CONTROL SCHEME OF THE PROPOSED WECS

The control conspire is created as per coordinate prerequisites of the WECS itself and the attributes of the proposed design. General control targets are recognized as: (1) MPPT in the full operation; (2) input capacitor voltage sharing of the particular converter; (3) least dc-interface current control; and (4) receptive power control. Fig. 6 shows the general control plan of the proposed WECS, where MPPT what's more, input capacitor voltage adjust control are accomplished with the generator-side converter while least dc-interface current what's more, responsive power control are controlled by the network side CSI. Every one of the images utilized as a part of the rest of this paper relate to those appeared in this figure.

A. Generator-side control

Two goals are controlled at the generator side: MPPT also, capacitor voltage sharing. In a variable-speed WECS, generator speed is changed in accordance with accomplish MPPT. MPPT strategies are broadly talked about in writing [3], incorporating MPPT with turbine control profiles, ideal tip speed proportions, and ideal torque control. The present examination principally concentrates on converter control; along these lines, the straightforward ideal tip speed proportion is connected to accomplish MPPT. In the event that the measured converter is perfect that all the included segments of the five constituent modules are indistinguishable, at that point the caught wind control is equitably circulated among them. The fell converter would thus be able to

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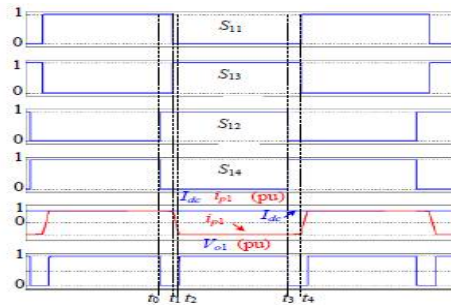


Fig. 4. Steady State waveform of Module 1.

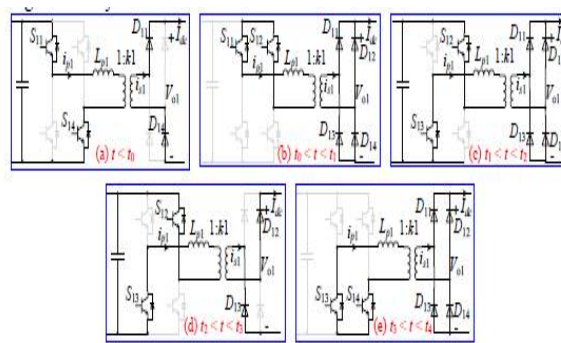


Fig. 5. Operation States of Module 1.

The controller output is indicated by torque reference T_{g_ref} of the generator, which is relative to the comparing generator current $I_{dc_generator}$. P and \square are the shaft matches and flux of the PMSG (Fig. 6). The required obligation cycle d_{common} for the dc-dc converter is acquired by contrasting $I_{dc_generator}$ and DC-connect current I_{dc} . MPPT is accomplished after applying the basic obligation cycle d_{common} to the dc-dc converter.

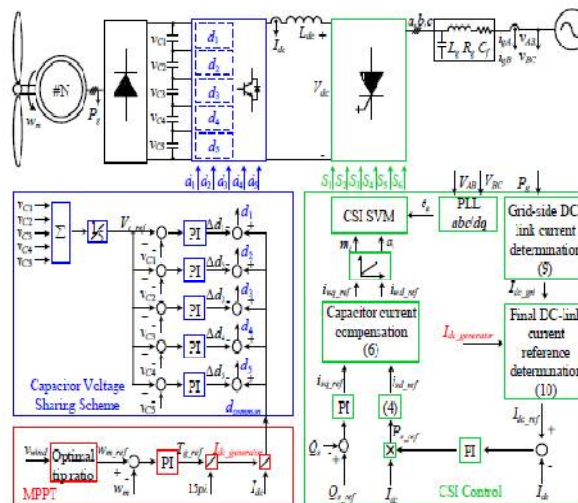


Fig. 6. Overall control scheme of the proposed configuration

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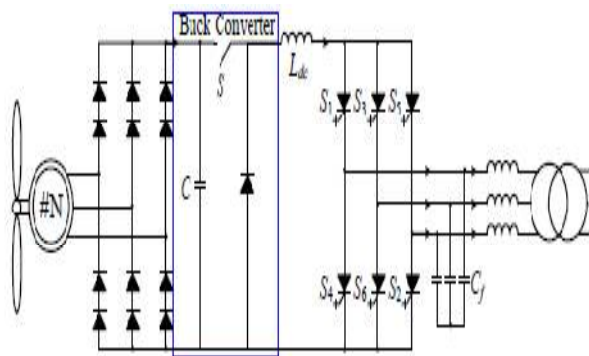


Fig. 7. Ideally simplified configuration of the proposed WECS

Along these lines, the identical circuit of the MFT-based fell dc-dc converter is determined appeared in Fig. 8, where input voltage V_{in} is the output voltage of the rectifier. I_{in} is the info current of the MFT-based fell dc-dc converter the dc-interface current; I_{dc} is spoken to by a steady current source. In this exploration, V_{IN} and I_{dc} are variable as indicated by various wind rates and consistent at a given speed.

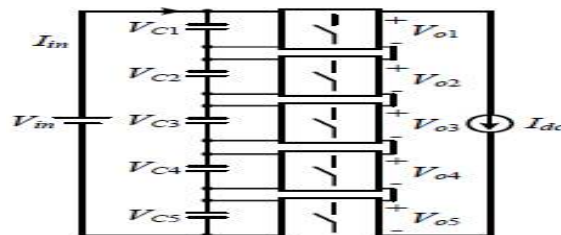


Fig. 8. Equivalent circuit of the MFT-based cascaded DC-DC converter

The MFT-based converter is associated in arrangement at the information also, the output. Such converters shares information and output streams I_{in} and I_{dc} , individually. Through power protection, the accompanying is gotten:

$$\begin{aligned}
 p_{in1} &= V_{C1} I_{in} = V_{o1} I_{dc} = p_{o1} \\
 p_{in2} &= V_{C2} I_{in} = V_{o2} I_{dc} = p_{o2} \\
 &\dots \\
 p_{in5} &= V_{C5} I_{in} = V_{o5} I_{dc} = p_{o5}
 \end{aligned}
 \tag{1}$$

Where V_{C1} , V_{C2} ... and V_{C5} , and V_{o1} , V_{o2} ... and V_{o5} are the harmony estimations of the info and output voltages of the constituent modules, separately. P_{in1} , P_{in2} ... and P_{in5} , and P_{o1} , P_{o2} ... and P_{o5} are the info and output energy of every module, separately. Accepting that the info capacitor voltage is adjusted.

$$V_{C1} = V_{C2} = V_{C3} = \dots \dots \dots V_{C5} = \frac{V_{in}}{5}
 \tag{2}$$

At that point, output voltage is consequently accomplished. Moreover, add up to power can be conveyed equally among every one of the modules. Consequently, we require just concentrate on input capacitor voltage sharing to accomplish both info/output voltages and power partaking in the MFT-based fell dc-dc converter. The constituent modules of the dc-dc converter basically have a place with a Buck converter with the accompanying information/output attributes:

$$\begin{aligned}
 V_{o1} &= f(d_1) V_{C1} \\
 V_{o2} &= f(d_2) V_{C2} \\
 &\dots
 \end{aligned}$$

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(3)

$$V_{O5} = f(d_5)V_{C5}$$

Where $d_1, d_2 \dots$, and d_5 are the obligation cycles and $f(d_1), f(d_2) \dots$, what's more, $f(d_5)$ are the voltage increases of every converter under relentless state.

Grid-side control:

The significant control goals for the lattice side CSI are dc-interface present and responsive power control. Dissimilar to in VSC-based WECS where dc-interface voltage is regularly controlled at a Consistent esteem, the dc-connect current in CSC-based WECS is arable as indicated by various levels of caught energy to limit misfortune. It is dictated by both the generator and the network side to accomplish (an) all the control destinations and (b) a least WECS misfortune.

As appeared in Fig. 6, dc-interface current control modifies the caught wind control while receptive power control is executed to direct responsive power as per the network codes. The Grid-voltage stage bolted circle (PLL) is utilized to produce a commotion free synchronous angle θ_g and angular frequency ω_g given the adjusted synchronous angle, the dynamic what's more, receptive power (P_s, Q_s) can be controlled autonomously by the accompanying:

$$P_s = 1.5V_{sd}i_{sd} \tag{4}$$

$$Q_s = -1.5V_{sd}i_{sq} \tag{5}$$

where V_{sd} and V_{sq} and i_{sd} and i_{sq} are the d- and q-axis components of the grid voltage and injected current. The reference current of the CSI i_{wd_ref} and i_{wq_ref} can be derived with the following,

$$i_{wd_ref} = i_{sd_ref} + i_{cd} = i_{sd_ref} - w_g C_f V_{cq} \tag{6}$$

$$i_{wq_ref} = i_{sq_ref} + i_{cq} = i_{sq_ref} + w_g C_f V_{cd}$$

Where i_{sd_ref} and i_{sq_ref} are the references of the d-and q-pivot segments of the infused network current. i_{cd}, i_{cq} and V_{cd}, V_{cq} are d-and q-pivot parts of the capacitor current and the voltage; these factors can be communicated as takes after:

$$V_{cq} = R_g i_{sd} + V_{sd} - w_g L_g i_{sq}$$

$$V_{cd} = R_g i_{sq} + w_g L_g i_{sd} \tag{7}$$

Where L_g and R_g speak to the matrix side line inductance and resistance, individually. Without misfortune thought of the converter, the caught wind control is equivalent to the matrix infused control

$$P_s = P_g \tag{8}$$

With considering the most extreme tweak record as $m_i = 1$, the base dc-interface current I_{dc_grid} controlled by the grid side CSI can be determined in light of (4)–(8):

$$i_{dc_grid} = \sqrt{\left\{ \left(1 - w_g^2 L_g C_f\right) \left(\frac{2}{3} \frac{P_g}{V_{sd}}\right) - w_g R_g C_f \left(\frac{2}{3} \frac{Q_{s_ref}}{V_{sd}}\right) \right\}^2 + \left\{ \left(1 - w_g^2 L_g C_f\right) \left(\frac{2}{3} \frac{Q_{s_ref}}{V_{sd}}\right) + w_g C_f V_{sd} + w_g R_g C_f \left(\frac{2}{3} \frac{P_g}{V_{sd}}\right) \right\}^2} \tag{9}$$

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Therefore, the final minimum dc-link current reference I_{dc_ref} , is expressed as:

$$I_{dc_ref} = \max(I_{dc_grid}, I_{dc_generator}) \tag{10}$$

Where $I_{dc_generator}$ is the base dc-interface current dictated by the generator-side, as showed in Fig. 6.

V.FUZZY LOGIC CONTROLLER

Fuzzy logic control is a non-mathematical decision algorithm that is based on an operator’s experience. This type of control strategy is suited well for nonlinear Systems. Fig.9 shows the structure of the fuzzy logic control algorithm.

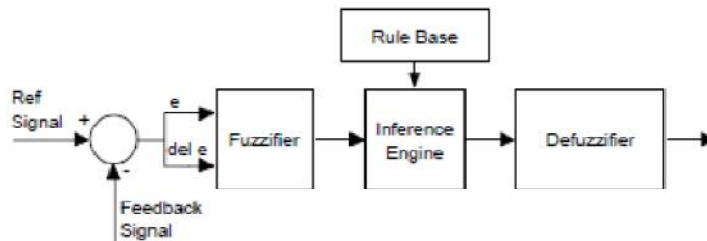
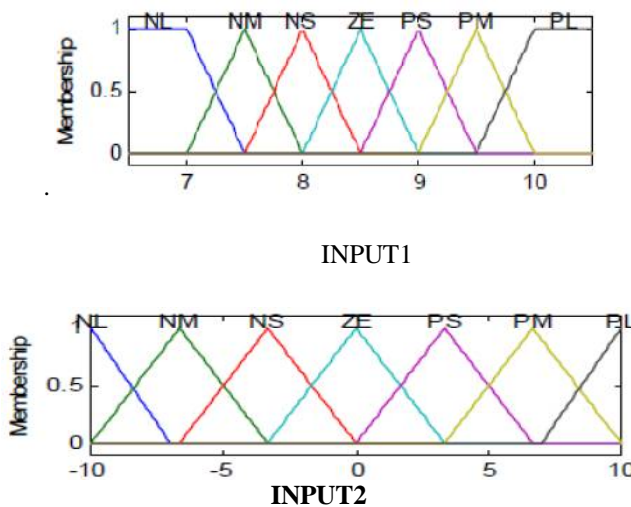


Fig.9. Structure of Fuzzy Logic Controller.

A. Fuzzifier Fuzzy logic uses linguistic variables instead of numerical variables. In a closed loop control system, the error (e) between the reference voltage and the output voltage and the rate of change of error (de/dt) can be labeled as zero (ZE), positive small (PS), negative small (NS), etc. In the real world, measured quantities are real numbers (crisp). The process of converting a numerical variable (real number) into a linguistic label (fuzzy number) is called fuzzification. Fig.7 shows the membership functions that are used to fuzzify the inputs.



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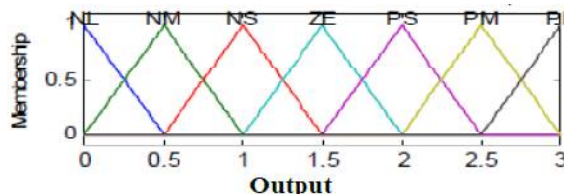


Fig.10. Membership Functions

The Fuzzy Logic Controller the inputs are mapped into these membership functions and a degree of membership is found for how much the input belongs to that particular linguistic label. The membership can take on a value from zero to unity for each of the linguistic labels. The waveforms are evenly distributed about the range of operation of the variables. For each of the input and output variables, the following seven linguistic labels are assigned to the membership functions: NL = Negative Large NM = Negative Medium NS = Negative Small ZE = Zero PS = Positive Small PM = Positive Medium PL = Positive Large Once the membership is found for each of the linguistic labels, an intelligent decision can be made to what the output should be. This decision process is called inference.

The rules of a fuzzy logic controller give the controller its intelligence, assuming the rules are developed by a person who has a experience with the system to be controlled. A programmer with more experience with the system will create a better controller. From this desired goal, rules are made for every combination of voltage and rate of change of voltage on what the output should be in order to stabilize. It is convenient when dealing with a large number of combinations of inputs, to put the rules in the form of a rule table.

Rules	NL	NM	NS	ZE	PS	PM	PL
NL	PL	PL	PL	PL	PL	PM	ZE
NM	PL	PL	PM	PM	PM	ZE	NS
NS	PL	PM	PS	PS	PS	NS	NM
ZE	PL	PM	PS	ZE	NS	NM	NL
PS	PM	PS	NS	NS	NS	NM	NL
PM	PS	ZE	NM	NM	NM	NL	NL
PL	ZE	NS	NL	NL	NL	NL	NL

Fig.11. Fuzzy Logic Rule Table.

VI. SIMULATION

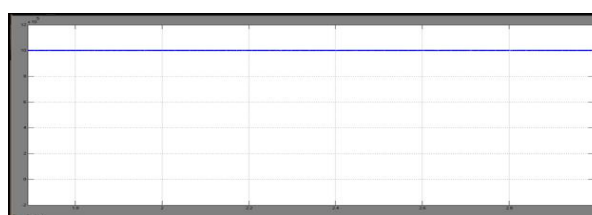
The proposed control scheme is verified by using MATLAB/SIMULINK software.

SIMULATION RESULTS USING PI CONTROLLER:

Case1:

The proposed configuration can be verified under condition of with and without voltage balancing control.

Before $t = 2$ s, the system operates in steady state with voltage balance control. At $t = 2$ s, the voltage balance control scheme is deactivated (all five modules operate under the common duty cycle d_{common} [Fig. 6]). At $t = 2.5$ s, the voltage balance control scheme is reactivated and input capacitor voltages quickly converge to nominal values.



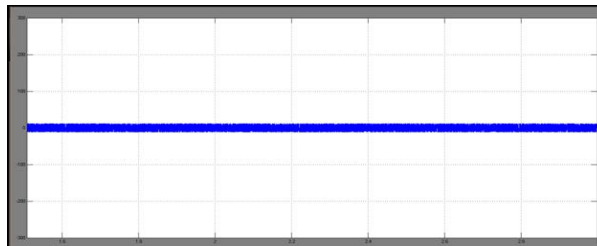
Real power(Ps)

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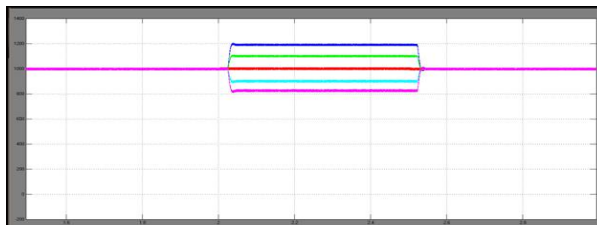
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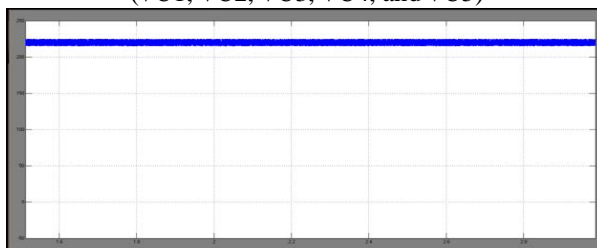
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Reactive power (Qs)



(VC1, VC2, VC3, VC4, and VC5)



Dc-link current I_{dc}

Case2: The proposed can be verified under condition of step change in wind speed. wind speed is purposely set to step down and up from 12 m/s (1 pu) to 10 m/s (0.833 pu) at $t = 2$ s and from 10 m/s (0.833 pu) to 12 m/s (1 pu) at $t = 4$ s, respectively.



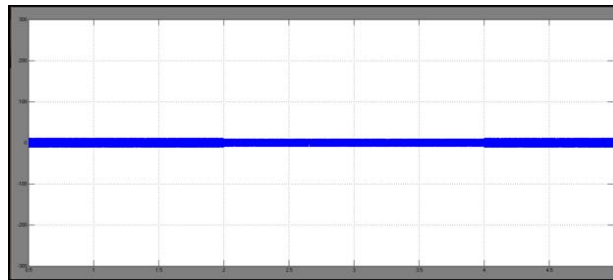
Active power (Ps)

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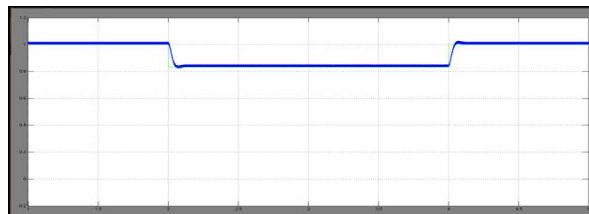
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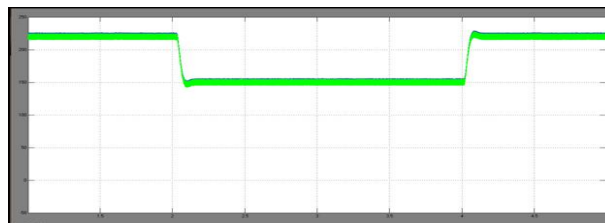
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Reactive power (Q_s)

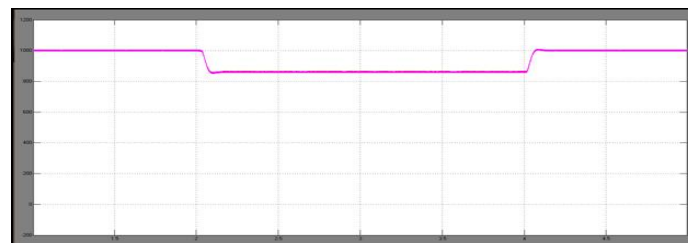


Reference and real speed of the PMSG (w_{g_ref}, g)



Reference and real speed of the PMSG (w_{g_ref}, g);

Dc-link current (I_{dc}, I_{dc_ref});



($VC1, VC2, VC3, VC4,$ and $VC5$).

Case3:

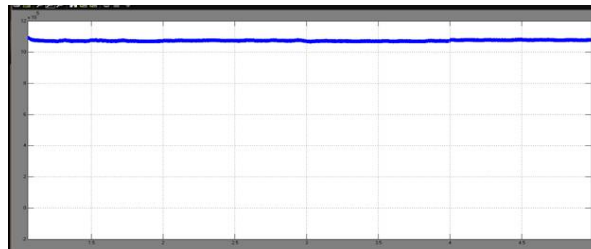
The proposed can be verified under condition of reactive power control. Reactive power Q_s is injected into the grid according to grid codes [3] with 330 kVA (0.33 pu) between 2 and 3 s, -330 kVA (-0.33 pu) between 4 and 5 s, respectively.

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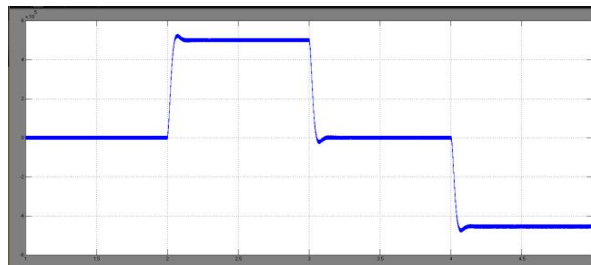
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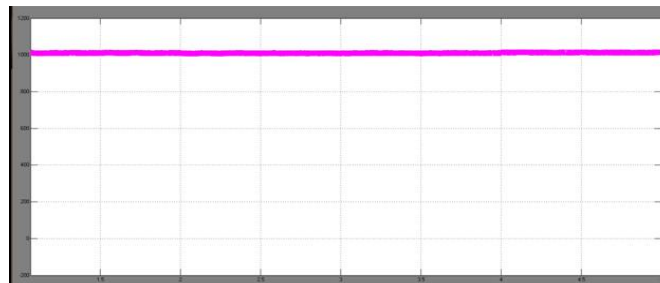
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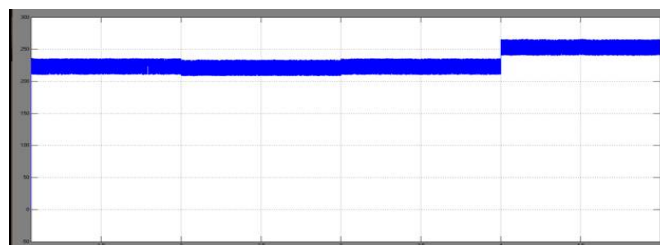
Active power (P_s)



Reactive power (Q_s)



(VC_1 , VC_2 , VC_3 , VC_4 , and VC_5).



Dc-link current (I_{dc})

SIMULATION RESULTS USING FUZZY CONTROLLER:

Case1:

The proposed can be verified under condition of with and without voltage balancing control. Before $t = 2$ s, the system operates in steady state with voltage balance control. At $t = 2$ s, the voltage balance control scheme is deactivated. At t

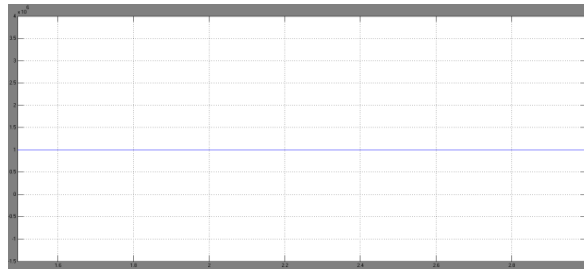
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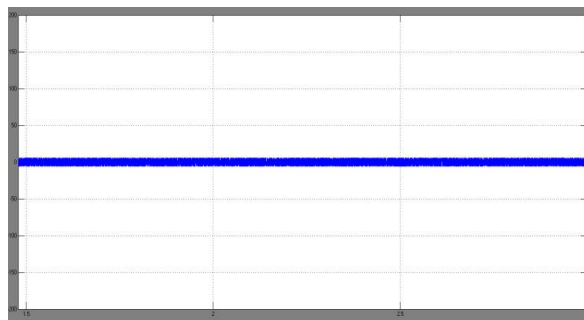
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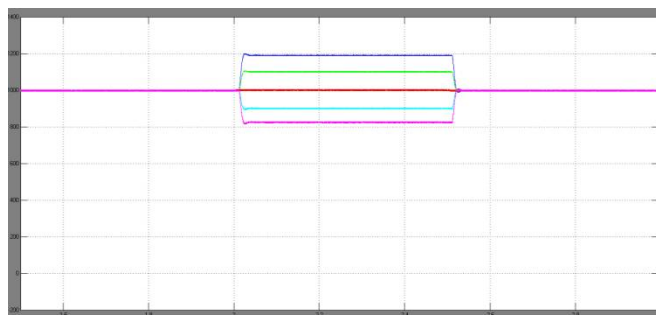
= 2.5 s, the voltage balance control scheme is reactivated and input capacitor voltages quickly converge to nominal values.



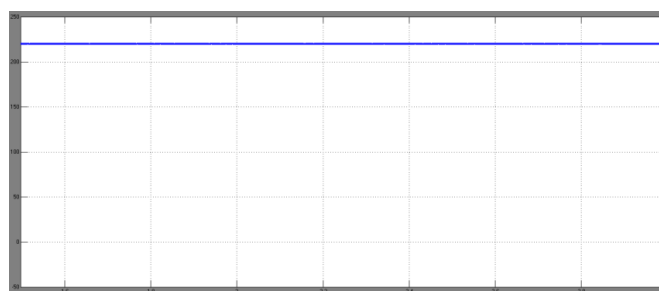
Real power(Ps)



Reactive power (Qs)



(VC1, VC2, VC3, VC4, and VC5)



Dc-link current I_{dc}

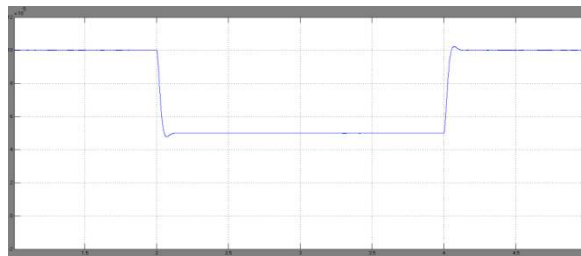
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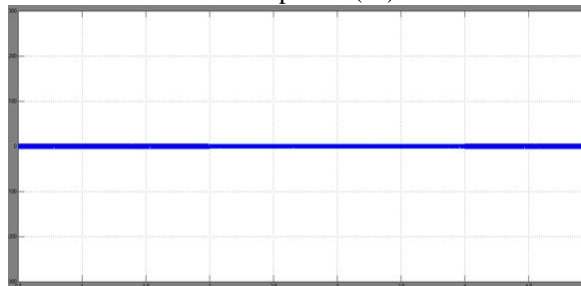
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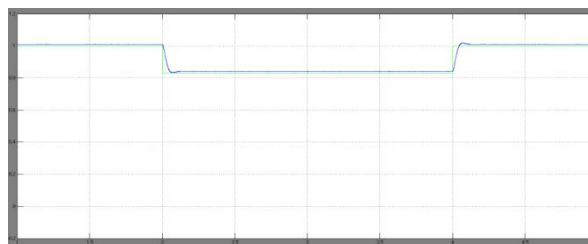
Case2: The proposed can be verified under condition of step change in wind speed. Wind speed is purposely set to step down and up from 12 m/s (1 pu) to 10 m/s (0.833 pu) at $t = 2$ s and from 10 m/s (0.833 pu) to 12 m/s (1 pu) at $t = 4$ s, respectively.



Active power (Ps)



Reactive power (Qs)



Reference and real speed of the PMSG (wg_ref, g);



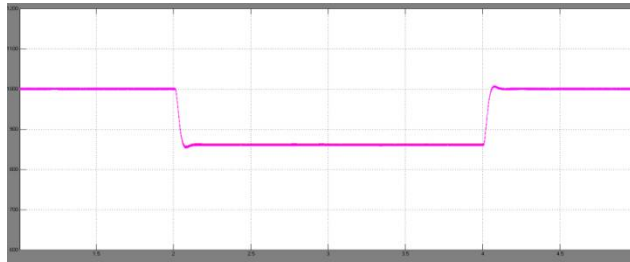
Dc-link current (I_{dc}, I_{dc_ref});

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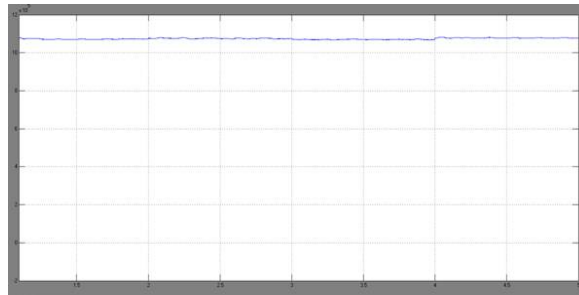
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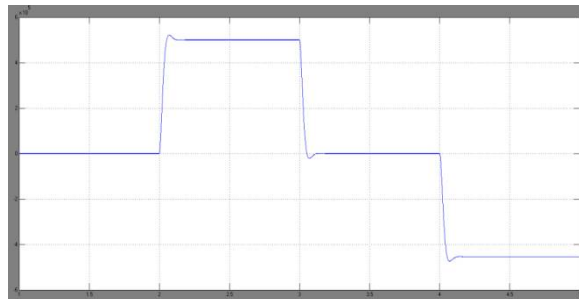


(VC1, VC2, VC3, VC4, and VC5).

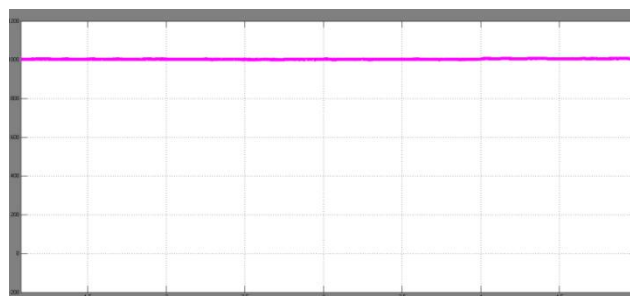
Case3: The proposed can be verified under condition of reactive power control. Reactive power Q_s is injected into the grid according to grid codes [3] with 330 kVA (0.33 pu) between 2 and 3 s, -330 kVA (-0.33 pu) between 4 and 5 s, respectively.



Active power (P_s)



Reactive power (Q_s)



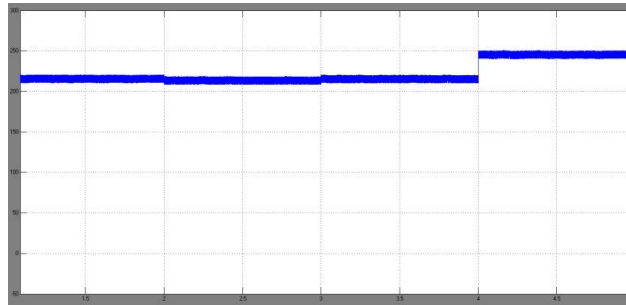
(VC1, VC2, VC3, VC4, and VC5).

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Dc-link current (I_{dc})

VII. CONCLUSION

In this paper, an MFT-based WECS is proposed for CSC-based offshore wind farms. The proposed configuration is composed of an MV PMSG, a passive rectifier, a modular MFT-based converter, and a CSI. The proposed method is analyzed using MATLAB/SIMULINK software. It is characterized by (a) no offshore substation; (b) high power density due to the adaption of a modular MFTs instead of a low-frequency transformer; (c) high reliability and flexibility due to the use of a modular converter; and (e) all the advantages of a CSC. From the above comparison of simulation results it is clear that fuzzy controller gives fast response than PI controller. Fuzzy controller has less rising and settling time than conventional PI controller and has better dynamic and steady state properties.

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