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MODEL PREDICTIVE CONTROL OF A PERMANENT MAGNET SYNCHRONOUS GENERATOR BASED ON A WIND ENERGY SYSTEM

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Abstract— *In this paper, the study of a model predictive control for a permanent magnet synchronous generator connected with a wind energy system. This paper presents a discrete model of the Permanent Magnet Synchronous Generator connected to a two-level voltage source converter, using a predictive algorithm to control the switching frequencies of the IGBTs and the design of an effective control on the wind turbine speed to effectively provide a new way to stabilize the generation side electrical output from variations of harsh wind changes that fluctuates due to weather-related wind speeds. The control algorithm is simulated in MATLAB, Simulink. The result of various wind speeds are presented to show the dynamic performance and efficiency of the proposed control approach. To demonstrate the accuracy of the models that were developed and the robustness of the speed controller design, several simulation results are presented and discussed.*

Index Terms— *Model predictive control, Voltage source converter, PMSG, Renewable energy system, Wind Energy system.*

I. INTRODUCTION

The ability to consistently generate reliable and consistent electricity is one of the most crucial elements in developing countries' progress in the modern period, which is driven by technology advancements in both the commercial and industrial domains. Therefore, in order to facilitate a nation's future economic developments, it is imperative that the expansion of power generation facilities be given top priority. Consequently, failure to adhere to changes, leads to the current infrastructure becoming strained when the link between electrical energy consumption and ongoing economic expansion is not balanced. Studies in [1] detailed, that "limited energy or electricity supply eventually leads to crippling all government operations and productive systems, freezing the economy, with higher rates of electrical theft, power outages, and people seeking other alternative means as the end results."

Conventional power generation methods are becoming less desirable due to their long-term environmental consequences, despite the requirement to stabilize generation capacity to continuously meet demand. As stated by research conducted, approximately one-third of emissions from fossil fuel combustion are attributed to power generation transports, Whereas, the remaining third is primarily caused by industry and residential heating [2]. With Fossil fuel combustion indicated as the largest single contributor to the greenhouse effect, the need to examine appropriate solutions for moving away from conventional methods to integrating existing infrastructure with alternative energy sources is required [27]. This demonstrated that Renewable energy sources (RES) are considered at the forefront of alternative energy sources due to their environmental benefits, which was validated in the study conducted at [2].

However, due to the varying nature and uncertainties of renewable sources, This poses challenges when considering an integration to the main grid [15]. For power generated utilizing a Permanent Magnet Synchronous Generators

(PMSG), studies conducted by [9], found that, wind turbines that operate near their manufactured rated value, tend to generate a power imbalance between both ends of the implemented converters (generator side and grid side) and causes the DC line voltage to rise over the permitted limit, potentially damaging the device and failing to meet requirements of grid regulations. This entails the need for additional control strategies for PMSG, implemented with the primary goal to balance supply and demand while achieving dependable performance.

A considerable amount of literature published on control systems for PMSG primarily focus on the use of other control strategies such as conventionally well-known controllers like PID control, Fuzzy logic, neural networks, and Maximum power point tracking [4],[17],[18],[19]. According to the results of a comparative study comparing PID and MPC, a PID controller performs best when there is only one input and one output (SISO), whereas an MPC controller is a more advanced method of process control used for MIMO systems, where the analysis demonstrated that the set-point in traditional control is far from constraint whereas the MPC set-point is closer to constraint [3] and it was proven that MPC tries to bring the process as close as possible to constraints without violating them. Much more exertion for viable model predictive algorithms for industrial process is still a necessity. An example is the study conducted in [4], to combine fuzzy logic with neural networks to tune the parameters of a PID excitation controller, however it was found that the duration of network development is extensive due requirement that neural networks need much more data than traditional machine learning algorithms. The paper by [5], presented an approach on application for model predictive control theory of a synchronous generator, controlling the voltage and active power where the performance of the MPC algorithm was compared to that of feedback linearization, PID and sliding mode. The researchers found that the MPC model-based control slightly reaches a faster response compared to the feedback linearization control and Slide mode control. Moreover, in their study, the more traditional PID based control was found to be quite slower than the compared counterparts due the combination of its two inner control loops of the speed and power. Several researchers have also conducted studies on Back-to-Back Voltage conversion of wind turbine systems, however, with very little reference to model predictive controllers. Majority of research on Back-to-Back HVDC systems focused on utilizing controls such as MPPT, PID and other controls discussed methods for maximum power extraction [6]- [7]. The study by [20], carried out a thorough review by giving the key methods utilized to regulate a PMSG applied in wind power conversion systems, ranging from traditional to contemporary control design. Four controls were evaluated, slide mode control (SMC), Direct Power control (DPC), Backstepping control (BSC) and Model Predictive control (MPC). SMC and DPC results in a chattering problem of a high-power oscillation caused by the discontinuous function used in the SMC structure and the hysteresis controllers used in the DPC design. the results also shows that predictive technique is a little slower than that of SMC, BSC, and DPC control which are characterized by a fast response. The time delay is due to the excessive computational load of the MPC technique.

One effective way of effectively controlling a permanent synchronous generator connected to a wind turbine system is controlling the speed. According to work done by researchers [8], on the control of PMSG, most research that focuses on the use of a three-phase diode rectifiers with an uncontrolled dc link and the use of a two-level voltage source converter generator side lacks adequate research work that accurately relates to modeling and control. In this research study, a Model Predictive control for a permanent magnet synchronous generator is examined with respect to attaining reliable performance and a balanced supply. The paper is organized as follows: Section two discusses the Permanent magnet synchronous generator, examining the formulation and theory. The Grid side voltage converter for the proposed study is further discussed in Section 3. Section 4 further provides an analysis on the Model predictive control, gives the conclusion of the overall study. Section 5 presents an examination on the generator speed control, with Section 6, providing the simulations.

II. PERMANENT MAGNET SYNCHRONOUS GENERATOR

The proposed MPC control utilizes a PMSG that can be characterized by an equivalent circuit shown in Figure 1, represented in the d-q reference frame of a three-by-three element matrix to simplify the analysis.

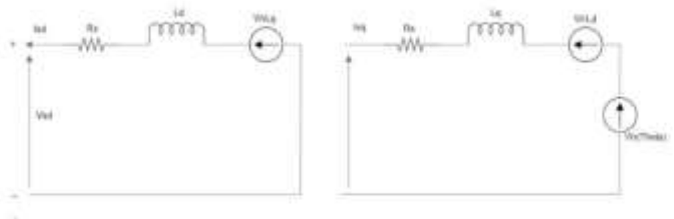

Figure 1. PMSG in d-q reference frame model.

The d-q synchronous rotation reference frame in Figure 1, has the capability to transform a three-phase system's time-domain components in an abc reference frame into direct, quadrature, and zero components in a rotating reference frame through the Park Transform, which transforms the AC current and voltage waveform into DC signals, applying two transforms sequentially making computations easier. The parks transform implements the change from a-phase to q-phase as represented in matrix form by:

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} sin\theta & sin\left(\theta - \frac{2\pi}{3}\right) & sin\left(\theta + \frac{2\pi}{3}\right) \\ cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (1)$$

The three-phase (abc) signal is transformed into a rotating reference frame (dq0) represented by, Figure 2, using Park transformation from an abc to dq0 block where input ωt, in rad, provides the spinning frame's angular position and in exchange an inverse Park transform is used by the d-q to abc to transform a dq0 rotating reference frame to a 3-phase abc signal. The following d-q values are produced by a positive-sequence signal with magnitude = 1 and Phase angle = 0˚ when the rotating frame alignment at ωt = 0 is 90˚ behind the phase A axis: d = 1, q = 0 s [10] :

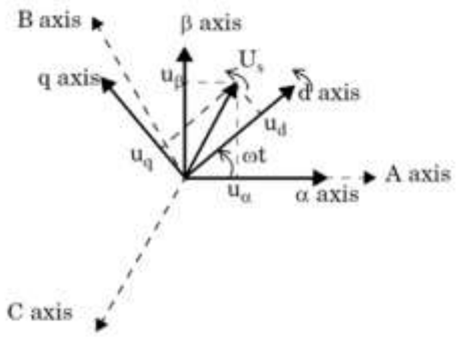

Figure 2: Rotating reference frame diagram.

$$V_d = \frac{2}{3}(V_a Sin(\omega t) + V_b sin(\omega t - \frac{2\pi}{3}) + V_c sin(\omega t + \frac{2\pi}{3}) \quad (2)$$

$$V_q = \frac{2}{3}(V_a cos(\omega t) + V_b cos(\omega t - \frac{2\pi}{3}) + V_c cos(\omega t + \frac{2\pi}{3}) \quad (3)$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \quad (4)$$

Where the instantaneous voltages are found by:

$$V_a = V_d\, sin(\omega t) + V_q\, cos(\omega t) + V_0 \quad (5)$$

$$V_b = V_d\, sin\left(\omega t - \frac{2\pi}{3}\right) + V_q\, cos\left(\omega t - \frac{2\pi}{3}\right) + V_0 \quad (6)$$

$$V_c = V_d\, sin\left(\omega t + \frac{2\pi}{3}\right) + V_q\, cos\left(\omega t + \frac{2\pi}{3}\right) + V_0 \quad (7)$$

The d-q frame alignment at t = 0 determines the conversion from abc to dq0 and the following relationships are attained when the rotating frame is lined up with the phase A axis

The following equations can be used to compute the active and reactive powers expressions:

$$P_{genrator} = \frac{3}{2}[(V_{sd} \times i_{sd}) + (V_{sq} \times i_{sq})] \quad (8)$$

$$Q_{generator} = \frac{3}{2}[(V_{sd} \times i_{sq}) + (V_{sq} \times i_{sd})] \quad (9)$$

Electric equations expressed in the rotor q-d frame.

$$\frac{d}{dt} i_d = \frac{1}{L_d}(V_d - R.i_d + L_q p \omega_m i_q) \quad (9)$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} V_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} p \omega_m i_q - \frac{\lambda p \omega_m}{L_q} \quad (10)$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q) i_d i_q] \quad (11)$$

$$L_{ab} = L_d + L_q + (L_q - L_d) \cos\left(2\theta_e + \frac{\pi}{3}\right) \quad (12)$$

Mechanical Torque Expression:

$$\frac{d}{dt} \omega_m = \frac{1}{J}(T_e - T_f - F\omega_m - T_m) \quad (13)$$

$$\frac{d\theta}{dt} = \omega_m \quad (14)$$

Wind turbine Power Expression:

$$P_{wind} = \frac{1}{2} \times \rho \times S \times V_{\omega^3} \quad (15)$$

$$P_{turbine} = C_p(\lambda, \beta) \times P_{wind} = \frac{1}{2} \times \rho \times S \times V_{\omega^3} \quad (16)$$

Where:

$$\frac{1}{\lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (17)$$

$$\lambda = \frac{\omega_m r}{V_w} \quad (18)$$

$$C_p(\lambda, \beta) = C_1\left(\frac{c_2}{\lambda} - c_3 \times \beta - c_4\right) e^{\frac{-c_5}{\lambda}} + c_6 \times \lambda \quad (19)$$

III. GRID SIDE VOLTAGE SOURCE CONVERTER

The Voltage Source Converters (VSC) implemented is the self-commutated converter that links the HVAC and HVDC systems utilizing high-power electrical devices such as IGBTs, where its ability to independently control the reactive and actual power flow at each of the AC systems to which it is connected, called the Point of Common Coupling (PCC), is the key feature of VSC-HVDC transmission [25], in this instance, unlike line commutated HVDC transmission, which reverses the DC current to change the flow of power, the polarity of the DC link voltage is maintained.

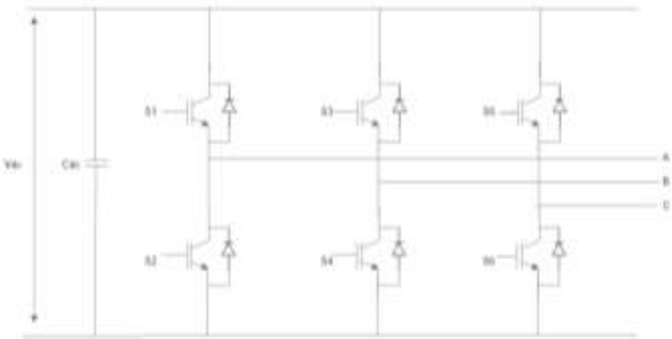

Figure 3: Voltage Source Converter

Figure 3, shows the two-level voltage source converter analyzed for implementation. Several advantages make the predictive control suitable for control of power converters, for instance, MPC is easy to understand and implement and can also be applied to different kinds of voltage source converters.

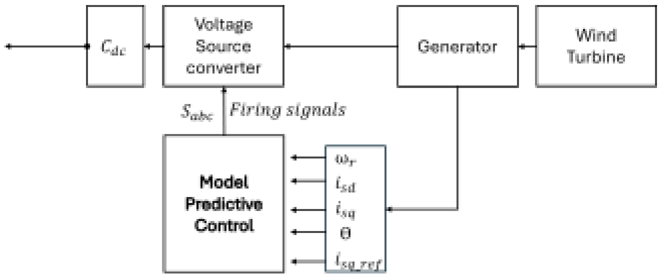

Figure 4: Block diagram of Grid Side VSC using MPC

The suggested configuration for the proposed MPC PMSG control is presented through a block diagram in **Figure 4**: Grid side voltage source converters, where the generator side arrangement of the voltage source converters is studied for the control of the power flow in the connection. For the control of PMSG to be feasible, the produced wind flow correlated to the PMSG at different speeds must be considered, as well as the converter's DC link voltage. The generator-side converter in this system modulates the speed of the PMSG to apply MPC control. The grid-connected converter in the meantime manages the active and reactive electricity supplied to the grid.

In Figure 5, I(kt) is the reference current for the predictive current control, and i(k+1) are the anticipated values of the m-states for the n potential switching states at time k+1. To minimize the cost function, the difference between the reference and anticipated values is determined, and the switching state that minimizes the cost function is chosen [26]. The optimal voltage vector from among the seven is chosen to minimize the computing work that results in various options. Choosing the optimal voltage vector among the seven presenting a control of the 2-level VSC, a straightforward cost function is constructed in absolute value term with one prediction step and n-prediction steps, respectively [11]. The generator-side converter the system modulates the speed of the PMSG applying MPC control algorithm [12], that was intended for stable DC input voltages on a conventional stable supply. However, in this study, the algorithm is applied for real-world applications and optimized to take a look at improving control of the generator-side connected VSC outputs applicable to manage the active and reactive electricity supplied to the grid regardless of variations in wind speeds in a wind turbine system connected to a permanent magnet synchronous generator.

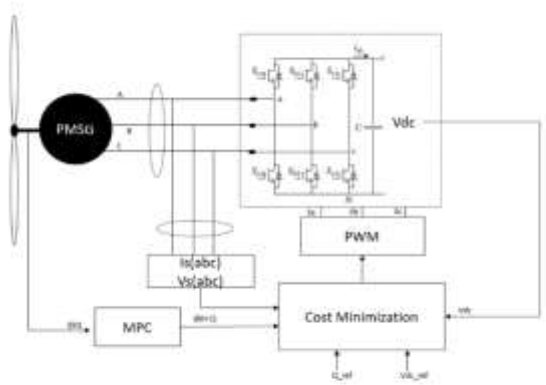

Figure 5: MPC control of PMSG.

IV. MODEL PREDICTIVE CONTROL

The main objective of the Model predictive controller as depicted in Figure 6, is to calculate the Input reference r (t) of the Permanent Magnet Synchronous Generator such that the PMSG output y(t) follows a desired speed by using a feedback mechanism to correct the error for optimization. The predictive control aims to obtain that certain desired performance even in the presence of disturbances and internal variations [23]. Figure 7 depicts the objective of the MPC to find the best predicted path that is the closest to the reference in a systematic way. K denotes the optimal time step where K+1 show the first implemented step. K continuously moves towards predict horizon K+P for re-optimization of the control from K+1. By solving the optimization problems, the MPC controller minimizes the error between the reference and predictive path of the output of the PMSG. Every step reruns the entire optimization forward in time for some start window to evaluate the best possible input.

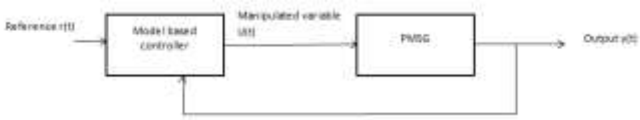

Figure 6: MPC model base and optimization.

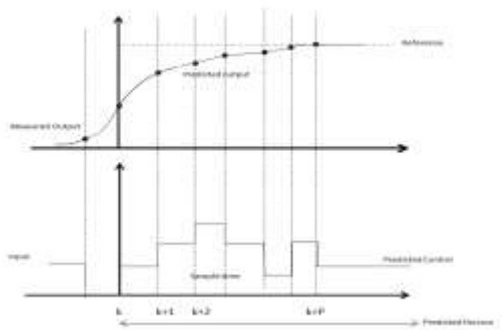
Figure 7: MPC set time graph.

The mathematical representation of Figure 7 is given by:

$$j = \sum_{i=1}^{P} w_e e_{k+i}^2 + \sum_{i=0}^{P-1} w_u u_{k+i}^2 \tag{20}$$

Equation (20), The Predictive path of the smallest cost function J gives the optimal solution and the Design Parameters for MPC that are dependent on the following:

I. Sample time

II. Prediction Horizon
III. Control Horizon
IV. Constraints
V. Weight

All these parameters affect the performance of the controller and the complexity of the MPC algorithm which solves an optimize the problem at each time step. This is done taking into consideration the problems of controlling multi-variable non-linear systems, due to physical and operation constraints on input systems systematic nonlinear control methods such as feedback linearization, that leads to very elegant solutions. The concept of optimal control, and in particular its practical implementation in terms of Nonlinear Model Predictive Control (NMPC) is an attractive alternative since the complexity of the control design and specification increases moderately with the size and complexity of the system [21].

Continuous formulation of NMPC is presented by the mathematical formula below where (21) denotes the nonlinear model and F= (x, u), the cost function that is non-quadratic (22) is the nonlinear constraints

$$x_{k+1} = f(x_k, U_k) \quad (21)$$

$$y_k = g(x_k) \quad (22)$$

The x(k) controls the u(k) and output y(k) which are vectors. Subject to input and state constraints of the form:

$$u(t) \in U, \forall t \geq 0 \quad (23)$$

$$x(t) \in X, \forall t \geq 0 \quad (24)$$

Here x(t)ϵR^(n) and o(t)ϵR^(m) denote the vector of state and input, respectively. Furthermore, the input constraint set U is compact and X is connected. For example, U and X are often given by box constraints of the form:

$$U := \{u \in R^m | u_{min} \leq u \leq u_{max}\} \quad (25) \qquad x := \{x \in R^n | x_{min} \leq x \leq x_{max}\} \quad \mathbf{(26)}$$

With the constant vectors u(min),u(max) and x(min),x(max)

The input applied in NMPC is based on the finite horizon open loop optimal control probe which is solved at every recalculation.

$$\min_{u(.)} J(x(t), \bar{u}(.)) \quad (27)$$

With the cost functional

$$j(x(t), \bar{u}(.)) := \int_t^{t+T} F(\bar{x}(\tau), \bar{u}(\tau))d\tau \quad (28)$$

x¯˙(τ)=f (x¯(τ),u¯(τ)),(x)¯(t) = x(t) (29)

$$\bar{u}(\tau) = \bar{u}(t + Tc), \forall \tau \in [t + Tc, t + Tp] \quad (30)$$

$$\bar{x}(\tau) \in X, \forall \tau \in [t, t + Tp] \quad (31)$$

Here Tp and Tc are the prediction and the control horizon with Tc <= Tp. The bar denotes internal controller variables and **x**¯(·) s the solution of (7) driven by the input signal **u**¯(·) : [t, t + Tp]→U under the initial condition x(t) [24]. The difference in the predicted and the real values is due to determination of the applied input via a re-optimization (over a moving finite horizon Tc) at every recalculation instant [17], [22]. The cost functional J is defined in terms of the stage cost F, which specifies the performance. The stage cost can for example arise from economic and ecological considerations. Often, a quadratic form for F is used:

$$F(x,u) = (x - x_s)^T\, Q(x - x_s) + (u - u_s)^T\, R(u - u_s) \qquad (32)$$

X(s) and u(s) Denote a desired reference trajectory that can be constant or time varying. The deviation from the desired values is weighted by the positive definite. Matrices Q and R. In the case of a stabilization problem (no tracking), xs = us=constant, one can assume, without loss of generality that (xs, us) = (0,0) is the steady state stabilize.

V. GENERATOR SPEED CONTROL

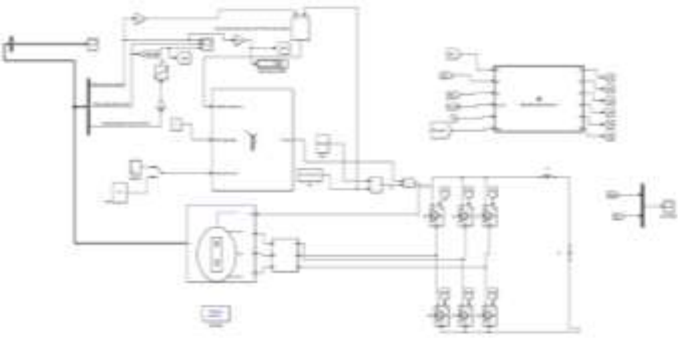

Figure 8: Simulink MPC Control of PMSG

The wind turbine model in Figure 8, is simulated first with a constant wind speed that is uncontrolled, with the results in Figure 9, showing an uncontrolled rotor speed input of the wind turbine model oscillating on and off. Under Control in, Figure 10, the predictive control allows for the control of different speeds with the control of the out speed following every change in input from the step function as indicated. This simulation uses the model predictive control algorithm to regulate the PMSG. To determine whether the recommended control schemes meet the study's objectives, this section looks at the model's execution results. To do this, MATLAB/SIMULINK simulation software is used to analyze the results on the wind energy conversion system coupled with a permanent magnet synchronous generator. Therefore, the analyses is directed towards the efficiency of the model predictive controls effectiveness to safeguard the wind turbine generator from hurtling and causing a mechanical stresses through changes when at high wind speeds. The general results concerning the control of the input speed on the wind turbine are also discussed including the DC link voltage control fluctuations and, Furthermore, future expansions of the model is discussed.

The wind turbine model in Figure 9, is simulated first with a constant wind speed that is uncontrolled, at a stop time of T=0.04 sec, with the results in Figure 10, showing an uncontrolled rotor speed input of the wind turbine model oscillating on and off. Under Control in, Figure 10, the predictive control allows for the control of different speeds with the control of the out speed following every change in input from the step function as indicated. This simulation uses the model predictive control algorithm to regulate the PMSG.

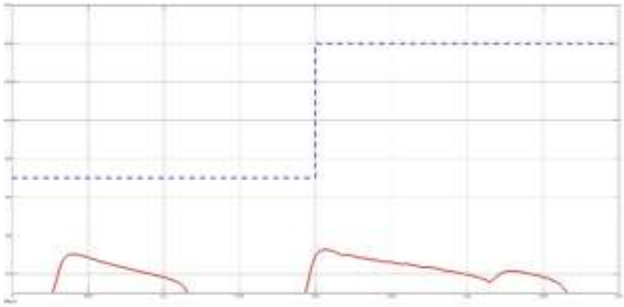

Figure 9: We (rad/s) uncontrolled.

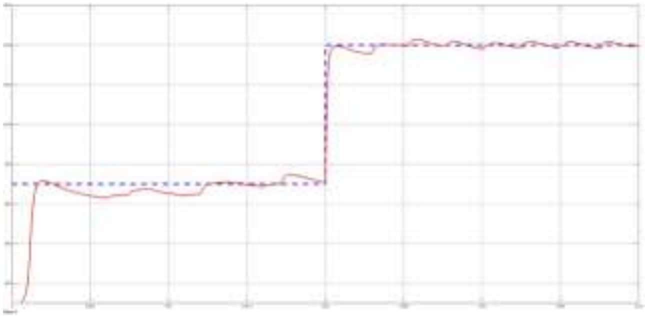

Figure 10: We (rad/s) controlled.

VI. VOLTAGE SOURCE CONVERTER SIMULATION

The oscillating Vdc voltage shown in Figure 11, simulated at a stop time of T= 1 sec increases with increase in wind speed and can be improved by the utilization of a VSC connected with a filter circuit on the DC side to smoothen the output. The two level voltage source converter in Figure 5, operates based on the concept that no two switches in the same leg can be turned on at the same time, this can be presented by following definition, written as [28].

$$S_k = \begin{Bmatrix} 1 & upper & IGBT & on \\ 0 & upper & IGBT & off \end{Bmatrix} \quad (33)$$

The power relationship between the AC side and DC side of a balanced three-phase system is as follows, this is if theoretically, the power switch resistances is ignored:

$$V_{dc} = \frac{\sum_{k=a,b,c} i_{kg}(t).V_{KN}(t)}{i_{dc}(t)} \quad (34)$$

$$i_{dc}(t) = i_{ag}(t)Sa + i_{bg}(t)Sb + i_{cg}(t)Sc \quad (35)$$

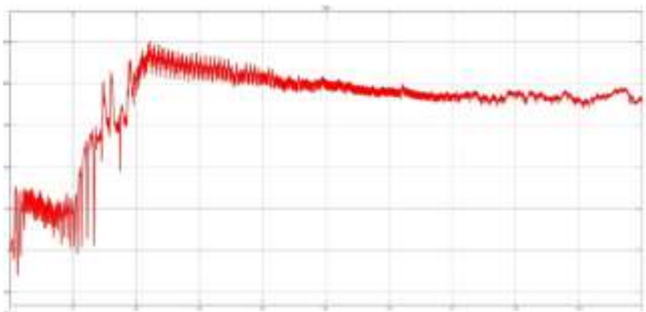

Figure 11: Vdc Voltage

The link capacitor Cdc can be found using Kirchhoff's laws when applied to the positive node:

$$C\frac{dV_{dc}}{dt} = S_a i_{ag} + S_b i_{bg} + S_c i_{cg} - \frac{V_{dc}}{RL} \quad (36)$$

Considering a balanced 3-phase system:

$$V_a + V_b + V_c = 0 \quad (37)$$

$$i_{ag} + i_{bg} + i_{cg} = 0 \quad (38)$$

As a result, the three-phase voltage source converter model represented in the ABC reference frame is made up of (39) and (40) through (41) which are rewritten as follows [11]:

$$C\frac{dV_{dc}}{dt} = S_k i_{kg} + i_L \quad (39)$$

$$L_g\frac{di_{kg}}{dg} + R_g i_{kg} = V_k - V_{dc}\left(S_k - \frac{1}{3}\sum_{j=a,b,c} S_j\right), k = a, b, c \quad (40)$$

$$\sum_{k=a,b,c} V_k = \sum_{k=a,b,c} i_{kg} \quad (41)$$

Figure 12, Figure 13, Figure 14 respectively give the Generator speed, electromagnetic torque and Stator Currents showing the changes that occurs when there is a variation of wind simulated at T=.1 sec, with a discrete settling time of 2e-6, where the Generator speed adjusts in changes to the wind turbine speeds fluctuations. the change in wind speed inputs in Figure 10 can be seen to correlate with the output of the generator speed in Figure 12. The characteristics of the wind turbines with a model predictive control and the study demonstrated show how the model can be utilized and designed to produce the most effective DC link voltage with a faster response time, that can be applicable to Back-to-Back HVDC systems even in the presence of varying wind speeds, controlling and optimizing the variations.

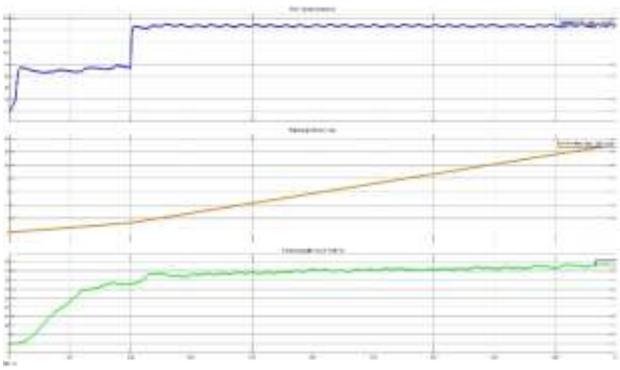

Figure 12: Generator Rotor speed, Rotor angle and Torque.

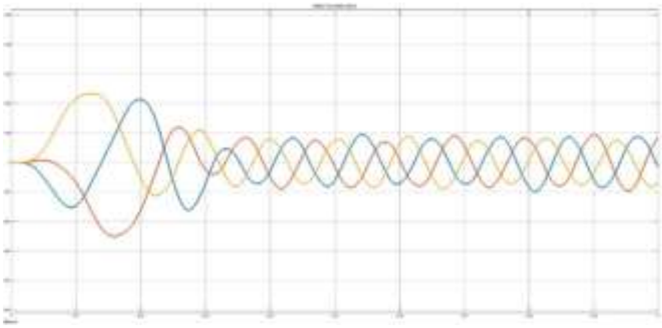

Figure 13: Stator currents.

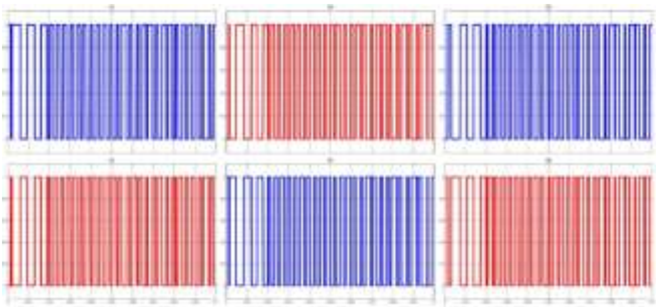

Figure 14: Firing signals of VSC.

Demonstrated in Figure 14, is the generation method of pulsing used for commutating each converter switch. This covers all the phases A, B, and C, where as stated in equation (40), switches S1, S3, S2, S4 and S5 and S6 of phase a functions in a complimentary way in a 2-level VSC structure. This indicates that turning on S1 prevents S3, turning on S2 prevents S4 from turning on, turning on S5 prevents S6 from turning on, and so on for the remaining phases b and c. This chapter examined the findings from.
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VII. Conclusion

The design of a wind turbine connected to a permanent magnet synchronous generator was studied and comprehensive simulation model was provided respectively. The discussion also analyzes the effectiveness of using a predictive controller to control the input speed and the generator side of the voltage source converter to optimize the DC link voltage as to assure a consistent provision of power flow generated from the permanent magnet synchronous generator. Additionally, the two-level voltage source converter as a means of converting the AC generated to Vdc link voltage that can be connected to an HVDC system is analyzed and the simulations results are presented in this study. Furthermore, improvement suggestions onto future work are given and may be successfully applied in future research.

VIII. References

[1] D. Mulongoti, BKumwenda, and B. Kumwenda, "Determining the effects of load-shedding on residential electricity consumption using meter data," in Global Humanitarian Technology Conference, Seattle University, Seatle, WA, USA,, 2016.

[2] M. Steen, "Greenhouse gas emissions from fossil fuel fired power generation systems," European Comission: Institue for Advanced Materials, Joint Research Centre, pp. 1-61, 2000.

[3] V. Balaji and L. Rajaji, "Comparative study of PID and MPC controller using LAB VIEW," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 2, no. 11, pp. 5545-5550, 2013.

[4] R. Gong, H. Yang, H. Wei, X. Meng and L. Xie, "Design of PID excitation controllers for synchronous generators based on fuzzy RBF neural network," International Conference on Electrical Machines and Systems, pp. 122-127, 2008.

[5] A. Bonfiglio and M. Invernizzi, "Model Predictive Control Application for the Control of the control of a grid-connected synchronous generato," nternational Electrical Engineering Congress (IEECON), pp. 1-4, 2018.

[6] J. M. Lakshmi,, K. S. Babu and P. M. Babu, "PMSG based wind energy conversion system for maximum power extraction.," Second International Conference on Computational Intelligence and Communication Technology, pp. 366-371, 2016.

[7] p. S. Silva, D. de V Mota, F. P. Ruiz, L. R. Cavlcant, L. T. Medeiros, V. S. Teixeira and A. B. Moreira, "Power Control and Harmonic Current Mitigation from a Wind Power System with PMSG," IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC),, pp. 1-6, 2019.

[8] M. Gannoun, J. Arbi-Ziani, M. W. Naouar and E. Monmasson, "Speed Controller design for a PMSG based small wind turbine system," IEEE International Energy Conference (ENERGYCon),, pp. 550-555, 2020.

[9] L. Bor-Yuh, M. F. Tsai and C. S. Tseng, "Phase voltage-oriented control of a PMSG wind generator for unity power factor correction," Energies, vol. 13, no. 21, p. 5693, 2020.

[10] MATHWORKS, "MATHWORKS," THE MATHWORKS INC, 1994. [Online]. Available: https://www.mathworks.com/help/sps/powersys/ref/abctodq0dq0toabc.html.. [Accessed 01 JUNE 2023].

[11] A. Almaktoof, A. Mustafa , R. K. Atanda and M. T. E. Kahn, "Modelling and simulation of three-phase voltage source inverter using a model predictive current control.," International Journal of Innovation, Management and Technology, vol. 5, no. 477, p. 7535, 2014.

[12] R. khadem, "Mathworks," Matlab, 12 May 2014. [Online]. Available: https://www.mathworks.com/matlabcentral/fileexchange/46559-firstmpcpmsm-mdl. [Accessed 09 October 2023].

[13] T. Øyvang, B. Lie and J. G. Hegglid, "Model Predictive Control for Field Excitation of Synchronous Generators," in Proceedings of the 9th EUROSIM & the 57th SIMS, Oulu, Finland, 2018.

[14] J. Mitali, A.A. Mohamad and S. Dhinakaran, "Energy storage systems: a review," Renewable and Sustainable Energy Reviews, no. 91, pp. 109 - 125, 2018.

[15] B. R. Faisal, P. Das, S. K. Sarker and S. K. Das, "A survey on control issues in renewable energy integration and microgrid," Protection and Control of Modern Power Systems, vol. 4, no. 1, pp. 1-27, 2019.

[16] Z. Xinyin, Z. Wu, M. H, X. Li and L. G, "Coordinated control strategies of VSC-HVDC-based wind power systems for low voltage ride," Energies, vol. 8, no. 7, pp. 7224-7242, 2015.

[17] I. Pisica, M. Abbod, G. A. Taylor, and A. S. Al-Toma, "A comparison of PI and fuzzy logic control schemes for field oriented permanent magnet synchronous generator wind turbines.," IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), no. IEEE, pp. 1-6, 2017.

[18] H. Efheij , A. Albagul and N. Albraiki , " Comparison of model predictive control and PID controller in real time process control system.," 19th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA) , no. IEEE, pp. 54-69, 2019.

[19] N. F. Mohammed, E. Song, X. MA and Q. Hayat, "Tuning of PID Controller of Synchronous Generators Using Genetic Algorithm," International Conference on Mechatronics and Automation, pp. 1544-154, 2014.

[20] M. Btissam, H. El Alami, H. Salime, N. Z. Laabidine, Y. El Mourabi, S. Motahhi, M. Bouderbal, M. Karim and B. Bossoufi, "A Review on popular control applications in wind energy conversion system based on permanent magnet generator PMSG," Energies, vol. 15, no. 17, p. 6238, 2022.

[21] T. A. Johansen, "Introduction to non;inear model predictive control and moving horizon estimation," Seletcted topics on constraned and nonlinear control, vol. 1, no. 1, pp. 1-53, 2011.

[22] F. Zishan, L. Tightiz, J. Yoo and N. Shafaghatian, "Sustainability of the Permanent Magnet Synchronous GeneratorWind Turbine Control Strategy in On-Grid Operating Modes," Energies, vol. 16, no. 10, p. 4108, 2023.

[23] A. Riad, T. Rekioua, D. Rekioua and A. Tounz, "Robust nonlinear predictive control of permanent magnet synchronous generator turbine using Dspace hardware.," International journal of hydrogen energy, vol. 41, no. 45, pp. 21047-21056, 2016.

[24] F. Allgower, R. Findeisen and K. N. Zoltan, "Nonlinear model predictive control: From theory to application," Journal-Chinese Institute Of Chemical Engineers, vol. 35, no. 3, pp. 299-316, 2004.

[25] F. Schettler, H. Huang and C. Norbert, "HVDC transmission systems using voltage sourced converters design and applications," In 2000 power engineering society summer meeting (Cat. No. 00CH37134), vol. 2, pp. 715-720, 2000.

[26] M. Khatir, S. A. Zidi, S. Hadjeri and M. K. Fellah, "Using Voltage Source Converter (VSC) based HVDC Transmission Link for Supply a Passive Load.," 2nd International Conference on Electrical and Electronics Engineering ICEEE'08, pp. 59-64, 2008.

[27] K. T. Safwat and B. Mohga, "Reasons for shifting and barriers to renewable energy: A literature review," International Journal of Energy Economics and Policy, vol. 10, no. 2, pp. 89-94, 2020.

[28] K. A. Swain and K. S. Senapati, "Modeling and simulation of AC/DC grid side voltage source converter used in wind power generation system," International Conference on Circuits, Power and Computing Technologies, pp. 484-489, 2014.