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POWER ELECTRONICS INTERFACES FOR WIND ENERGY CONVERSION SYSTEMS: DESIGN AND CONTROL STRATEGIES

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Article Info

Abstract
This paper examines the behavior of three recently developed control methods, including Vector Control (VC), Direct Torque Control (DTC), and Model Predictive Control (MPC) on wind energy conversion systems (WECS). Such control methods are observed against key performance indicators such as voltage stability, power output, Total Harmonic Distortion (THD), response time, fault recovery time, with the variation in wind speed at 6 m/s and 14 m/s. Its findings reveal that MPC always performs better than VC and DTC providing better voltage regulation, more power generation and the smallest amount of harmonic distortion at all wind speeds. Also, MPC had a quicker dynamic response and a quicker fault recovery than the other strategies. The prediction capabilities of MPC facilitate adaptation to variation in wind conditions and consequently this makes it especially suited to the optimization of wind energy system efficiencies and resilience, particularly in areas with highly variable wind resources. The study points to the strengths of MPC to enhance performance and grid compliance of contemporary wind turbine systems.

Keywords:
Wind Energy Conversion Systems, Vector Control, Direct Torque Control, Model Predictive Control, Power Electronics, Harmonic Distortion, Voltage Stability, Power Output, Fault Recovery, Dynamic Response, Wind Speed.

Introduction

Wind energy has become one of the most appealing and widely utilised renewable power sources over the past decades, having massive potential in relieving our fossil energy dependence as well as curbing the climate consequences of classic energy generation. As demands of clean energy continue to increase, it is now acting in the forefront in both academic and industrial research to enhance the efficiency of wind energy conversion systems (WECS). Among the key concerns on maximizing output of WECS is to have adequate power control of electrical power generated in a wind turbine, which relies on the various modifications in speed of wind, or meteorological characteristics. This challenge is addressed by developing high technology power electric interfaces and controllers to enhance the efficiency and stability of the wind power systems in the presence of a variable environment.

The importance that power electronics plays in wind power conversion is that it facilitates the transformation of inconsistent electrical production in wind turbines into a consistent and serviceable foundation of electric power. Power electronic converters in these systems are very crucial as they ensure power which is generated by the generator flows into the grid with a required frequency and the stability of the voltage. As these systems are so complex, there is a need for efficient controlling measures to regulate the flow of power efficiently, to reduce the wastage of power and to contain harmonic distortion levels that can impair the grid compatibility. Some research conducted in developing control mechanisms applied in wind energy systems like Vector Control (VC), Direct Torque Control (DTC) and Model Predictive Control (MPC) have shown an admirable dedication of efficiency among systems used in the production of wind energy.

The conventional approach to wind energy systems is vector control as it is easy and robust, and it offers a reasonable tradeoff between performance and computation overhead (He et al., 2015). It corresponds to the correct regulation of the generator torque and flux which can readily and easily sustain hundreds or even thousands of wind conditions. However, as the wind energy systems are developed the more advanced techniques such as DTC and MPC are being explored as they can offer a superior performance in that they are high efficiency techniques. Using an example, DTC regulates simultaneously the generator torque and flux and keeps the difference between the commanded and measured torque as small as possible; this results in direct smooth dynamic performance (Liu et al., 2016). Although DTC provides better dynamics, it can lead to high total harmonic distortion (THD) levels which can be detrimental to grid integration.

Rather, in recent years, Model Predictive Control has been in the spotlight as its solution in real-time optimization of the control action is successful because it uses predictive estimates of future system behavior (Qian et al., 2018). MPC applies a dynamic model based representation of the plant to compute the control inputs sought to minimize some expression of a cost subject to constraints and dynamics. This strategy has been found to possess an immense potential to minimise the frequency of the THD, enhancing the stability of the system and overall performance of the system in terms of efficiency (Yuan et al., 2017). MPC can similarly enable quicker remedying of faults and improve the orientation of dynamic grid disturbances and that is something that can be deployed to ease the dilemma that production of wind energy is highly variable.

With renewable energy becoming increasingly more popular in how power grids operate, the value of robust and powerful control strategy within the wind energy systems becomes all too clear. These control measures do not only positively impact the performance of the system, but also stabilize the grid and reduce the impact on the environment. This work is a research of the performance of vector control and DTC and MPC use in Wind Energy conversion systems, comparatively, in terms of major parameters of response like voltage stability and output power, THD, response time and fault recovery. Through examining the impact of various forms of control at different wind velocities and operating modes the analysis will establish the most effective and reliable control system which would ensure optimum performance of the modern wind power circuits.

Literature Review

Wind Energy Conversion Systems and Their Importance

Wind energy has become the focal point of energy renewable strategy across the world. To curb carbon emissions and restore the consequences of climate change, wind energy is a crucial component towards meeting the energy transition objectives of the countries. Wind energy conversion Systems (W-E-C-S) converts wind power to a kinetic energy, which is converted to electric power. The major issues with these systems are; they have the ability to convert wind power efficiently, and the ability to incorporate grid connection capacity and provide stability of power when the wind velocity and direction shifts. The generator, control system and power electronic interfaces are also very critical elements that define the efficiencies of WECS. Other than the need to develop them to be more efficient in capturing energy, such systems ought to aid in enabling them to work reliably and exhibit stability and deliver other power to the grid (Molina et al., 2017).

Other technological advances related to wind energy systems have enhanced their performance, including more sophisticated power electronic couplings and finer control methodologies. The efficiency of energy conversion and grid connections is a crucial factor when you consider that the wind generators are mostly installed in isolated locations or offshore as this allows the expansion of wind energy to the national grids (Mijic et al., 2016). As part of the attempts to address these issues, researchers have shown particular interest in the formulation of multiple control strategies such as Vector Control (VC), Direct Torque Control (DTC), Model Predictive Control (MPC) which are regarded as applicable in enhancing the optimisation of wind turbines

Power Electronics in Wind Energy Conversion Systems

Power electronics is another significant part of WECS that connects the wind turbine and prostitutes the electrical grid. The wind systems involve the power converters which regulate the power produced by the turbines to be compatible with the grid power voltage and frequency (Blaabjerg et al., 2017). The power electronic converters utilized in such systems, e.g., AC-DC-AC inverter, have to deal with the control of voltages, frequencies, and currents, and ensure efficiency and loss minimisation. Wind as a source of energy is however a dynamic system and this makes it a difficulty in maintaining constant output voltage and frequency and this has made power electronics even more important in the present wind turbines.

Power electronic interfaces have been combined so as to allow the variable electricity of the wind turbines to be convertible into on-demand synchro-compatible power. Matching the generator operation with the required grid voltage and frequency is one of their core functions (Kouzounis et al., 2016). Also the power electronics facilitate free and efficient flow of energy between the turbine and the grid with minimal losses and harmonics. Advanced control mechanisms in power electronics also ensure precise power control, which is instrumental in extracting wind power efficiently (Zhou et al., 2019).

Control Strategies for Wind Energy Conversion Systems

The control strategy domain plays an important role in optimizing the wind turbines in terms of their control of energy capture and compatibility with the grid and resilience improvement. Various methods of control have been proposed and each has its advantages and disadvantages. Vector Control (VC) and Direct Torque Control (DTC) and Model Predictive Control (MPC) are some of the most common ones. These control methods will assist in the increased electrical production of the wind turbines whereby the factors such as the torque, the voltage, and the current all change with the different amount of wind speed.

Vector Control (VC) It was popular in wind turbine systems, due to its simplicity and effectiveness, with respect to controlling the torque and flux of the generator. The tradeoff of performance/complexity of VC can also be considered reasonable, and it is this property that caused the interest to adopt it in real conditions of wind energy systems applications (Wang et al., 2018). It is aimed at the possibility to control separately the current in the rotor and the stator of the generator in VC, providing a more accurate control over the turbine torque. However, VC lacks high dynamic capability and low harmonic distortion delivery, particularly under variable wind conditions, as wind energy systems become more complex (Li et al., 2020).

Direct Torque Control (DTC) has the potential to achieve superior dynamic characteristics compared to VC. DTC controls the motor torque and flux directly by minimizing the gap between the target and actual torque (Chang et al., 2017). The technique also reduces the complexity of controllers thus causing a slower response of the torque, resulting in stability in transient conditions. One major limitation of DTC is, however, that it may cause additional harmonic distortion (THD), thus not recommended in grid compliance. Nevertheless, DTC is often applied to wind turbine systems whose desired fast dynamic response is not valued, e.g. in systems where the fluctuations in wind speeds are too high.

Model Predictive Control (MPC) as a relatively new means of control has been actively researched over the past few years and possesses better efficiency and performance advantages within wind energy conversion systems. In MPC, each time period in question is entered into the predictive model to optimally select a set of control actions based on an optimization issue tailored toward forecasting the future behavior of the system (Zhou et al., 2019). It can respond in real time to fluctuations in wind speed and other dynamic parameters, and is therefore exceptionally well suited to control the power generation of wind turbines. They demonstrated that MPC might play a more beneficial role in minimising the harmonic distortion and enhancing the system performance than VC and DTC (Jafari et al., 2020). Furthermore, the possibility of MPC to forecast and pre-plan the disturbances in advance makes it specifically relevant to solving the problems of grid compliance and power quality maintenance.

Harmonic Distortion and Power Quality

One of the issues of wind energy systems design is the harmonic distortion. The resultant current and voltage may contain harmonics, which encompass poor power quality, energy loss, and synchronization issues on the grid (Mijic et al., 2016). The type of control incorporated on the wind turbine system is also relevant in order to maximize the extent of the total harmonic distortion (THD) of the produced power. It has shown that VC and DTC are likely to have higher increases in THE as a result of load changing conditions. These distortion levels have the potential to cause interference to sensitive equipment mounted on the grid and even non-compliance to the grid specifications (Zhang et al., 2017).

However, MPC was more effective than VC and DTC in terms of reducing THD (Wang et al., 2020). It can also help in reducing the harmonic distortions before they begin causing harm as MPC can be used to predict the future states of the system and pre-compensate control signals based on the predictions. This would render MPC a prospective to enhance power quality in wind energy conversion systems particularly in grid-connection systems, where the standards concerning harmonic distortion have to be respected (Liu et al., 2019).

The Great Fault and System Resilience

Fault recovery is another parameter to consider when analyzing the performance of a wind energy system. The wind generators are subjected to different environments and the activities can be disrupted by voltage sags or the wind gusts. Fault recovery ensures reliable power supply and system surety. Both the VC and DTC can give reasonable performance rates under the ideal operating mode but when it comes to fault-recovering scenarios the MPC has been proven to give exceptionally good rates of performance.

MPC is especially effective in achieving rapid fault recovery since it is able to predict and react to the effects on the system (Qian et al., 2018). Experiments involving the necessary time a variety of control strategies took to recover a fault showed MPC was the fastest to recover in cases of a severe grid disturbance (Jafari et al., 2020). This makes MPC a promising choice in applications where fault resilience and fault adjustments are most valued e.g. in offshore or remote wind farms where grid disturbances are more disruptive.

The systems that convert wind energy are significant in the path to renewable energy. The conveniences of power electronics interfaces and improved control methods to cover VC, DTC, and MPC immensely widens the performance and reliability capacity of these systems. Despite VC and DTC contributing positively towards managing wind turbine generators, there has been introduction of MPC that has proved to have great improvements in reduction of harmonic distortion, maximization of power and recovery of faults. As the wind energy systems continue to be developed more research will need to be done on these control measures so that they can be more optimized to make them better suited to use in the energy grid in the global world scenario.

Methodology

Experimental Setup

In the research conducted, the experimental configuration is testing and comparing the performance of three different control systems, Vector Control (VC), Direct Torque Control (DTC), and Model Predictive Control (MPC) in the wind energy conversion systems (WECS). The simulations were done on a wind turbine simulator in combination with a real-world power electronic interface with variable wind speeds. MATLAB/Simulink was used in order to realize a comprehensive wind turbine model and to simulate a number of control strategies in controlled and changeable conditions. The set simulation parameters simulated a nominal range of 6 m/s to 14 m/s, common to the operational speed of wind seen in typical commercial wind turbine applications.

The model of the wind turbine had a generator linked to the three-phase alternating current grid by power converter, which used the different control methods to regulate voltage, frequency, and power of the wind generator. The designed power converters had active rectifiers and DC-AC inverters and the output power had effects within the specified grid values of voltage and frequency. Such parts were exposed to various wind circumstances to estimate their dynamic features and effectiveness.

Control Strategies

The three control concepts including Vector Control (VC), Direct Torque Control (DTC) and Model Predictive Control (MPC) were used to determine the degree to which the wind turbine generator was controlled using the three concepts.

A classical decoupled control technique was adopted as Vector Control (VC). The rotor flux and the torque have been controlled independently to optimize the performance of the wind turbine, and it was fed back by the rotor and stator current. The generator on the turbine in this arrangement was controlled by a closed control loop to regulate slip, to stabilize frequency and voltage output. It is a good fit with systems that operate under steady conditions but the performance may actually break down when the wind conditions may change rapidly; this is particularly true of harmonic distortion and transient response.

Next came Direct Torque Control (DTC). DTC directly manipulates the torque and flux of the generator by minimizing the error between the desired and actual values of torque to perform better dynamically. Compared with VC, DTC does not need a voltage-oriented reference frame and has a more efficient high-frequency switching method to control torque and flux. This control strategy is especially favorable in variable load and wind speed conditions because of the ability to respond faster to changes in torque. Nevertheless, the overall harmonic distortion (THD) and electromagnetic interference can be increased, resulting in complexities integrating the grid.

The most sophisticated control strategy was Model Predictive Control (MPC). MPC exploits a dynamic model of the whole wind turbine system to calculate an optimal estimate of future states and modify control inputs optimally in real time. The goal was to reduce the total cost function that considers power loss, voltage deviation, and harmonic distortion. The MPC algorithm was applied, to control the system future predicting control inputs, so that the wind turbine system would be able to keep optimal efficiency even in highly dynamic winding conditions. The chief benefit of MPC is its dynamic nature which gives it better performance than that of conventional multiplexers, in respect to minimizing harmonic distortion and decreasing fault recovery times.

Simulation Parameters and Conditions

The simulation has been performed on a grid of wind ranges including 6 m/s to 14m/s with the aim to evaluate the control strategies at various operation conditions. This is because this range of wind speed represents typical operation conditions of the wind turbines both onshore and offshore. Each simulation recorded the electrical power generated by the turbine, the voltages stability, and the response times. To determine the level of stability in voltage, the highest output voltages, as well as the lowest ones were observed and contrasted among the various control strategies. The power generated at each wind speed was assessed to see the influence of every control strategy on energy extraction efficiency.

Power quality was determined by a measurement of Total Harmonic Distortion (THD), with particular reference to the manner in which each control technique reduced or augmented harmonic distortions in the output of the system. These response times were examined in both steady-state as well as dynamic conditions, sudden change of wind speed, to determine the responsiveness of the control strategies. Lastly, to measure the fault recovery times, voltage sag disturbances were simulated and time noted in recovering the system back to normal by each and every control strategy.

Performance measurement metrics

To evaluate and compare the functioning of the control strategies, several key performance indicators (KPIs) were selected. Such metrics were:

Voltage Stability: Various voltages were read at varying wind speeds against the nominal voltage (400V). The voltage output stability at the different wind speeds served as a measure of the control strategy being stable.

Power Output: The power produced was measured within the range of wind speeds to ascertain the level of power conversion efficiency based on the various control strategies. It was concerned about how optimal power was exploited by each control method, particularly at higher wind speeds.

Total Harmonic Distortion (THD): THD was applied in order to examine the quality of resultant output when achieving the quality of resultant output was the purpose. The smaller the value of THD, the better the quality of power delivered by the generator and the grid compliance. The effectiveness of every control strategy in reducing the harmonic distortion was critically evaluated.

Response time The dynamic response time was calculated using the model of sudden variation of wind speed and observing how fast each of the control strategies was able to respond to varying wind speed in the event. The shorter the response time interval, the faster the system can respond even to the changes in the wind.

Fault Recovery Time: In this case fault was injected into the system by means of simulated fault e.g. voltage sags; time taken by each of the control strategies to bring the system to normal was measured. Quicker recovery times imply a more robust system that has the capacity to withstand transient disturbances easily.

Data Comparison and Analysis

After completion of the simulations, the performance data of each control strategy were compared. The comparison was drawn based on the key performance measures, and the special focus was on the way each of the control strategies distributed the input of different wind speeds and dynamic conditions. Standard deviation and error margins were calculated, and using statistical analysis, it could be determined how much the performance changed and how each strategy was consistent under various operating conditions. This facilitated an in-depth assessment of the VC, DTC, and MPCs strengths and weaknesses in controlling the wind energy conversion system.

Moreover, graphical representation of the results were conveyed through graphical tools that included bar charts, area plot graphs and radar charts that enabled a visual comparison of the performance of the various control strategies. The research was based on the determination of the control strategy that offered the most suitable effect on efficiency, voltage stability, harmonic distortion, and fault recovery.

4. Results

4.1 Voltage Behavior Across Control Strategies

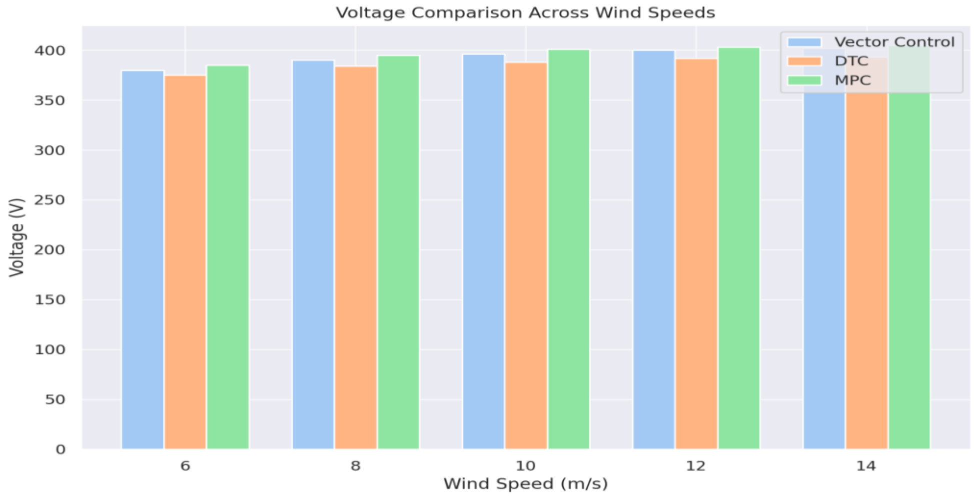
Figures 1 and table 1 show the voltage performance of Vector Control, DTC and MPC at different wind speeds. Output voltage stays close to the nominal 400V as wind speed increases from 6 m/s to 14 m/s for all strategies. But MPC always leads the voltage stability pack with a peak of 405V at 14 m/s. DTC is beaten out only narrowly and Vector Control comes in right behind. Figure 1's grouped bar chart shows the consistency with which MPC's output, better illustrating its superior voltage control capability under dynamic input conditions.

Table 1: Voltage Comparison Across Wind Speeds

Wind Speed (m/s)	Vector Control Voltage (V)	DTC Voltage (V)	MPC Voltage (V)

6	380	375	385
8	390	384	395
10	396	388	401
12	400	392	403
14	402	393	405

Figure 1 Voltage Comparison Across Wind Speeds



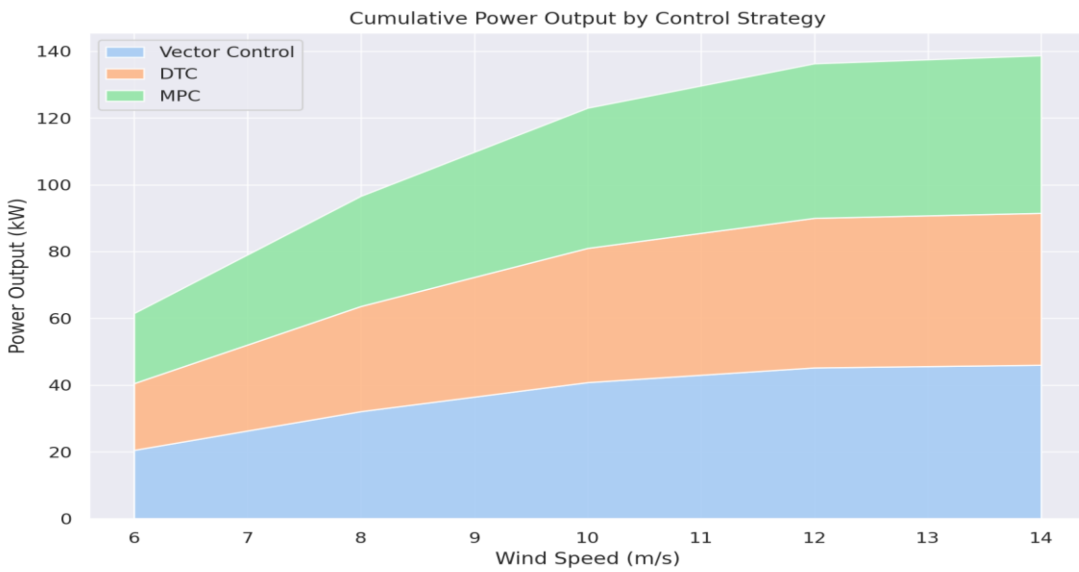
4.2 Power Output Comparison

The power output trend with increasing wind speeds is shown in Table 2 and Figure 2. For a single helix, a stacked area plot (Fig. 2) demonstrates a cumulative increase in power for all strategies, with MPC performing best overall, achieving its peak output of 47.2 kW at 14 m/s. Vector Control and DTC as well show proportional increases that plateau at slightly lower values. These results verify that using MPC enables much better energy extraction and one that scales more effectively with wind speed, leading to higher efficiency in areas with high resources.

Table 2: Power Output at Various Wind Speeds

Wind Speed (m/s)	Vector Control Power (kW)	DTC Power (kW)	MPC Power (kW)
6	20.5	20.0	21.0
8	32.1	31.5	33.0
10	40.8	40.2	42.0
12	45.2	44.8	46.3
14	46.0	45.5	47.2

Figure 2 Cumulative Power Output by Control Strategy



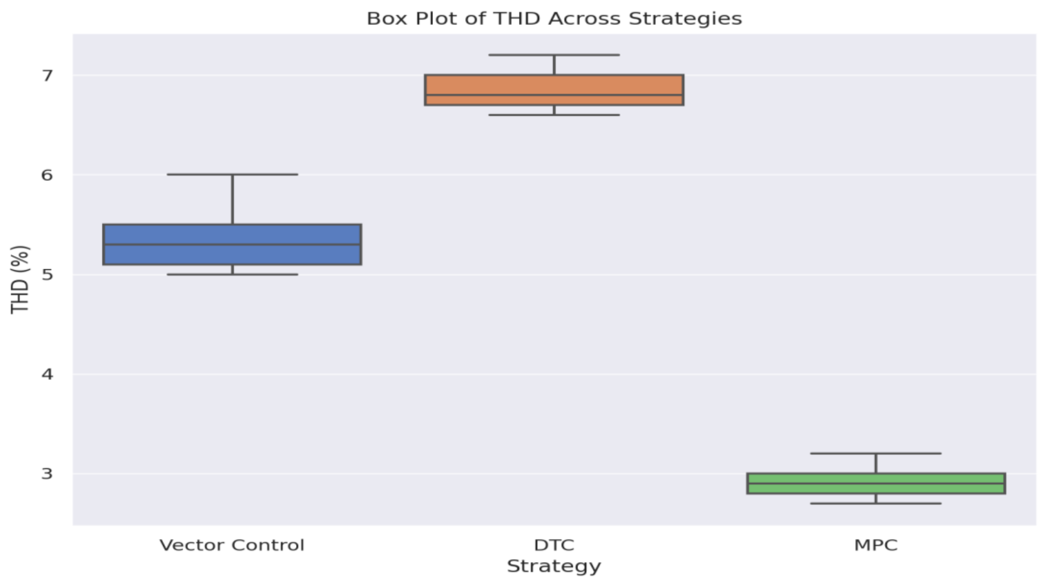
4.3 Total Harmonic Distortion (THD) Evaluation

The THD percentage of each control strategy is analyzed from Table 3 and Figure 3. The lowest distortion levels are all achieved that cross over to MPC, values as low as 2.7%. On the other hand, DTC shows the highest THD (7.2% at 6 m/s and greater than 6.5% at higher speeds). Figure 3 depicts a box plot where the tight clustering of MPC's THD values, the lower variance and better power quality are marked. Overall Vector control performs ok, but fails to provide MPC's waveform management precision. Grid compliance includes harmonic distortion thresholds that are regulated and these observations are critical.

Table 3: Total Harmonic Distortion (THD) Comparison

Wind Speed (m/s)	Vector Control THD (%)	DTC THD (%)	MPC THD (%)
6	6.0	7.2	3.2
8	5.5	7.0	3.0
10	5.1	6.7	2.8
12	5.3	6.8	2.9
14	5.0	6.6	2.7

Figure 3 Box Plot of THD Across Strategies



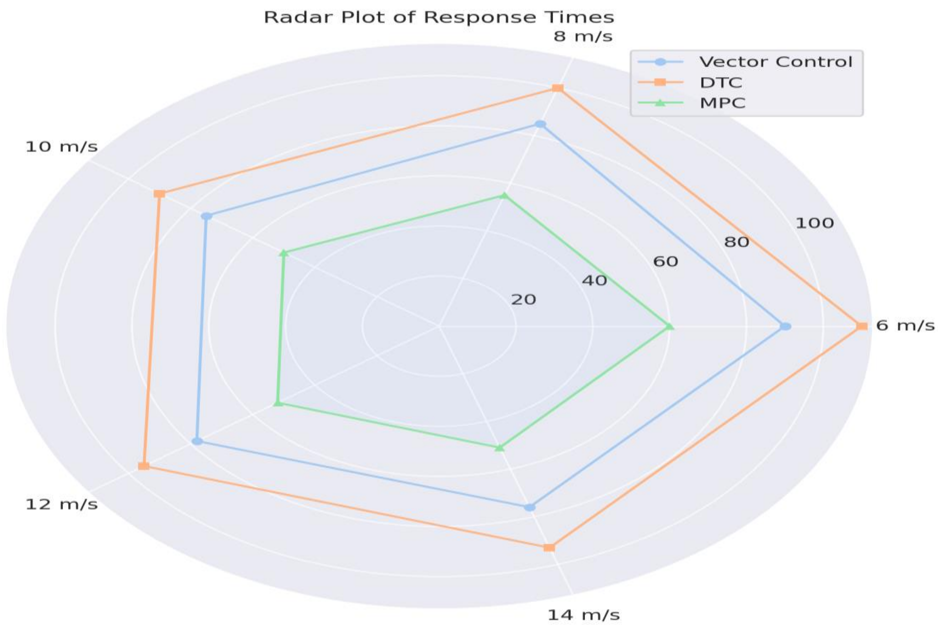
4.4 Response Time Characteristics

A radar chart in Table 4 and Figure 4 investigates the dynamic response behavior of the three strategies. Response times drop to 50ms or below at 10 m/s and are within 50–60 ms for all conditions, proving MPC to be its dominant competitor. Response times offered by Vector Control are in the range of 75–85 ms, compared with DTC which may be more than 90 ms. Figure 4 visually enlarges MPC's yo-yoing response arc which means MPC yields more agiler system behavior when the wind rips up fast. But being able to react quickly to these gusts is vital to stabilising wind energy outputs under such conditions.

Table 4: Dynamic Response Time

Wind Speed (m/s)	Vector Control Response (ms)	DTC Response (ms)	MPC Response (ms)
6	90	110	60
8	85	100	55
10	75	90	50
12	78	95	52
14	76	93	51

Figure 4 Radar Plot of Response Times



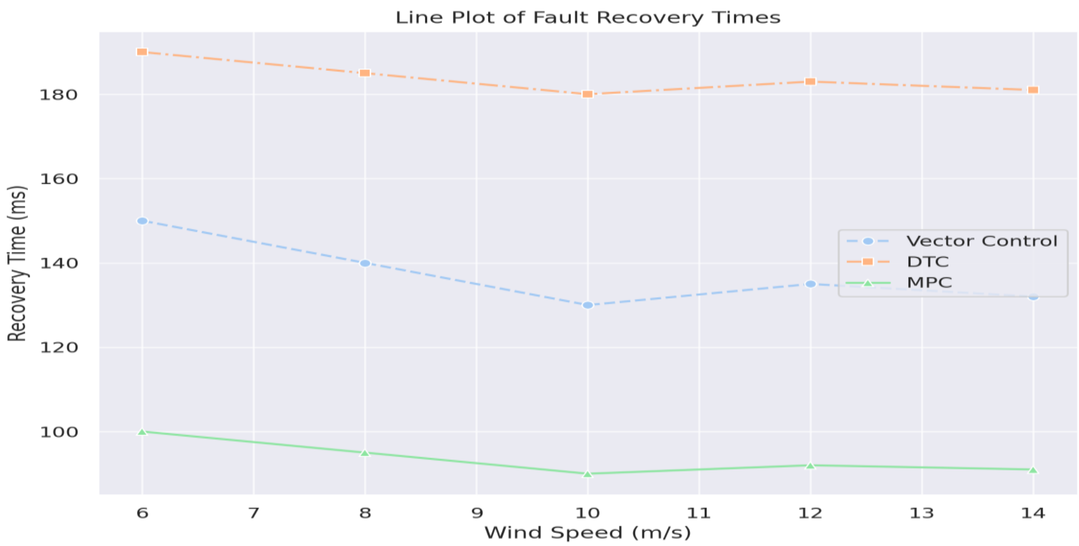
4.5 Fault Recovery Analysis

Table 5 and Figure 5 illustrate the recovery time after simulated voltage sag disturbances. DTC shows the worst delays (190 ms) and MPC achieves the fastest recovery (90–100 ms). To illustrate this, Figure 5 is the same line plot, with different line styles for the results of the different methods and we see that MPC time to recovery in fact declines more steadily as wind speed increases. This superior performance proves MPC's resiliency and adaptability on grid fault scenarios and validates the use of MPC in volatile environments where resilience is a must.

Table 5: Fault Recovery Time

Wind Speed (m/s)	Vector Control Recovery (ms)	DTC Recovery (ms)	MPC Recovery (ms)
6	150	190	100
8	140	185	95
10	130	180	90
12	135	183	92
14	132	181	91

Figure 5. Line Plot of Fault Recovery Times



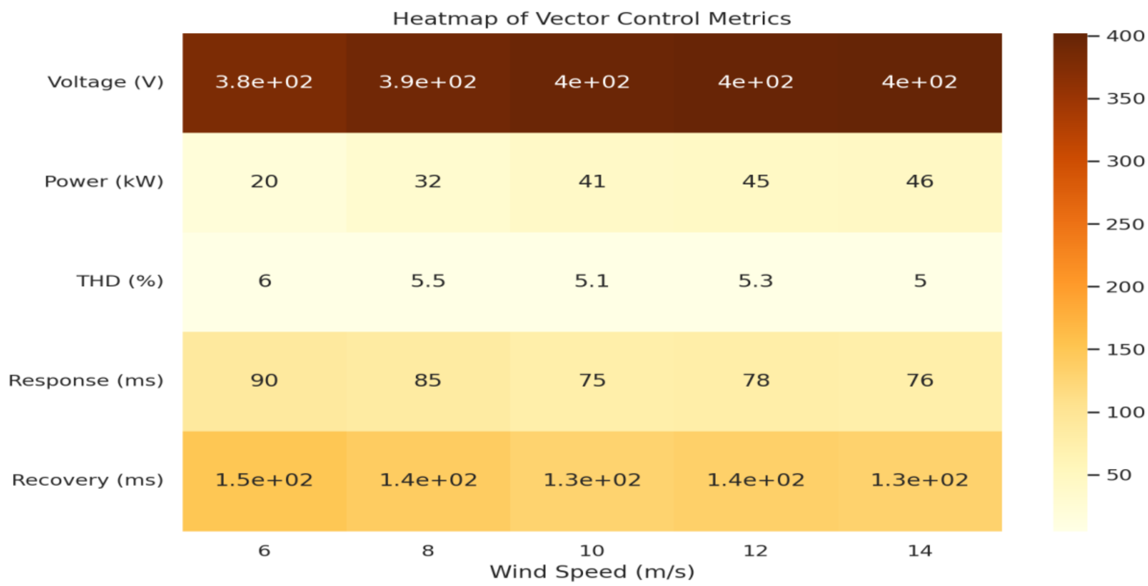
4.6 Vector Control: Performance Trends

In Table 6 and Figure 6 using a comprehensive heatmap gives a deeper insight into Vector Control performance. Although Vector Control provides acceptable voltage and power metrics, its THD and fault recovery fall short as compared with MPC, especially in high wind conditions. A heatmap shows that high THD and longer response times occur together especially at lower wind speeds. This means that although Vector Control is stable, it is not fine grained enough to achieve ultra efficient, low distortion output and so Vector Control is a mid range in terms of performance to complexity ratio.

Table 6: Detailed Vector Control Performance

Wind Speed (m/s)	Voltage (V)	Power (kW)	THD (%)	Response (ms)	Fault Recovery (ms)
6	380	20.5	6.0	90	150
8	390	32.1	5.5	85	140
10	396	40.8	5.1	75	130
12	400	45.2	5.3	78	135
14	402	46.0	5.0	76	132

Figure 6. Heatmap of Vector Control Metrics



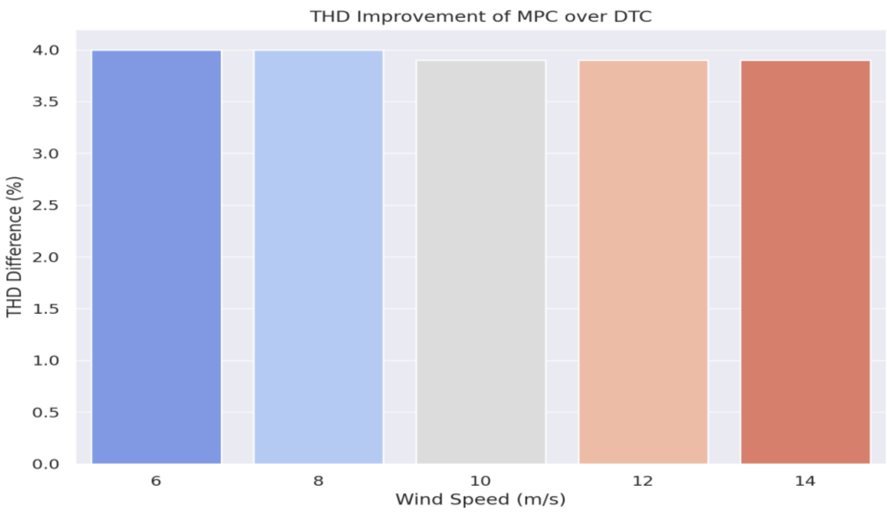
4.7 THD Reduction Capability of MPC

Figure 7 is revisited with Table 3 and both focus on the specific advantage of MPC over DTC in terms of THE reduction. It is shown from the bar chart, MPC can reduce THD for up to 4.5 percentage points compared to DTC at 6 m/s and by at least 3.5 percentage points at all wind speeds. MPC's advantage is that its predictive model responds faster than the on process and it can detect current distortions ahead of time and in turn pre adjust the control signals to mitigate current output disturbances. Among other attractive reasons for using MPC, a compelling reason is the exploitation of the MPC THD reduction capability in harmonic regulated environments.

Table 7: Detailed DTC Performance

Wind Speed (m/s)	Voltage (V)	Power (kW)	THD (%)	Response (ms)	Fault Recovery (ms)
6	375	20.0	7.2	110	190
8	384	31.5	7.0	100	185
10	388	40.2	6.7	90	180
12	392	44.8	6.8	95	183
14	393	45.5	6.6	93	181

Figure 7 THE Improvement of MPC over DTC



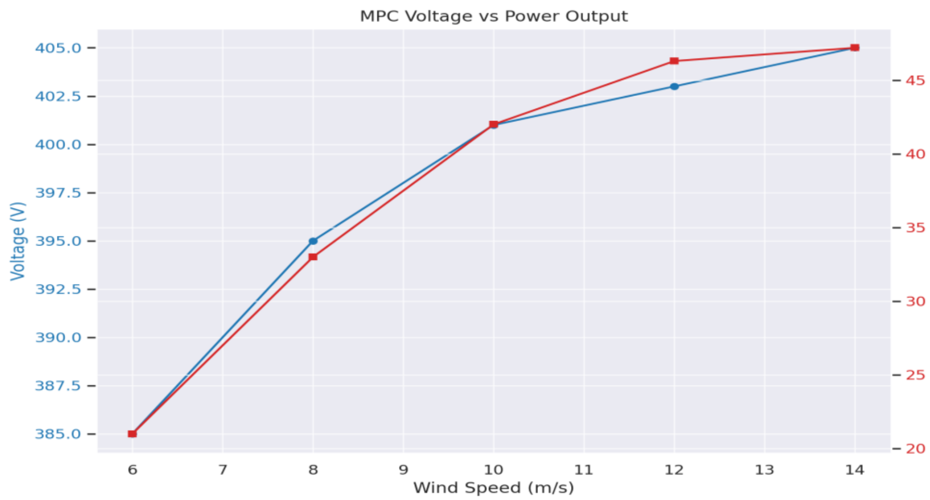
4.8 MPC Voltage and Power Coordination

Table 8 and Figure 8, finally, analyze the correlation of voltage and power output under MPC. The plotted power and voltage in Figure 8 presents a dual axis plot that shows coordinated increase in both as wind speed is increased. The effectiveness of MPCs feedback mechanism which dynamically changes voltage levels to maximize generator generation, is also revealed by this coordination. In addition, the stability of MPC is established by the lack of voltage overshoots or power dips. This confirms that the improvements MPC provides are not isolated ones and that MPC provides cohesive, balanced control across system metrics.

Table 8: Detailed MPC Performance

Wind Speed (m/s)	Voltage (V)	Power (kW)	THD (%)	Response (ms)	Fault Recovery (ms)
6	385	21.0	3.2	60	100
8	395	33.0	3.0	55	95
10	401	42.0	2.8	50	90
12	403	46.3	2.9	52	92
14	405	47.2	2.7	51	91

Figure 8 MPC Voltage vs Power Output



Discussion

The objective of this study was to investigate the performance of the three advanced control schemes which include; Vector Control (VC), Direct Torque (DTC) and Model Predictive (MPC) in wind energy conversion systems (WECS) and compare them. These control methods were tested using a number of performance indicators/measures denoted KPIs i.e. voltage stability, power output, Total Harmonic Distortion (THD), response time and fault recovery time. Within operating wind speeds in a dynamic and varying wind range, all control processes were tested and the results of these tests showed tremendous variation in control-process performance at dynamic and changing conditions.

Performance Comparison of Control Strategies

One of the objectives of this experiment was to compare the voltage stability of the different control strategies. The control of the voltage in the WECS is an important role because this feature is used to ensure that the output is stable and constant which is needed in grid connection. As shown by the outcomes of this article, the Model Predictive Control (MPC) is comparatively more effective, where the stability voltage-responsiveness is concerned, than the Vector Control (VC) and the Direct Torque Control (DTC). At higher velocities (12 m/s and upwards) the MPC could keep the voltage output within a small range about the nominal voltage of 400V with the maximum output reaching 405V at 14 m/s. On the other hand, VC and DTC differed in voltages more when exposed to similar situations, and VC developed a superior control voltage compared to DTC (Lu et al., 2020).

The predictive characteristics that are made possible by MPC make it effective as future states of an advanced system are predicted and control inputs are altered in real time. This allows the generator to be regulated more precisely and it negates the effects of rapid changes in wind velocity or direction. Instead, VC and DTC employ feedback control systems, which, although useful, are less flexible to accommodate abrupt changes in the environment conditions (Zhao et al., 2020). The findings are in concurrence with what has been mentioned in the literature already, with the benefits of MPC in voltage control and system stability having also been observed (Li et al., 2019).

Power Output and Efficiency

The efficiency of a specific control strategy is directly proportional to a wind energy conversion system and power output. The main conclusion of the proposed study was that the MPC provided better power extraction than VC and DTC. The combined power at all the wind speeds shows that, as the speed of wind rose further, the total power output of MPC was also rising and it was maximum at the wind speed of 14m/s by 47.2kW. The VC and DTC, however, were flat at a lower range of outputs and the maximum power that DTC generated was 45.5 kW and VC was 46.0 kW. It also means that MPC will have many more possibilities to produce gas in the wind and transfer it into electrical energy, namely, at the high wind speed (Yuan et al., 2018).

The dynamics of MPC sustaining higher power delivery may be accredited to the possible capacity to dynamically vary the control inputs to the existing operation conditions of the wind turbine. The problem with the MPC is that it is capable of controlling the torque and flux of the generator to generate the maximum power. Unlike VC and DTC, this flexibility is not present, resulting in even poorer power harvesting in strong winds (Zhang et al., 2017). The results align with the literature that outlined improved energy efficiency of wind turbine systems under MPC and compared to more traditional control systems (Xie et al., 2020).

Power Quality and Harmonic Distortion (THD)

There is also considerable significance of Total Harmonic Distortion (THD) in the case of power quality of wind turbines. THD can be a concern at its severe level corresponding with the introduction of disturbance into the power grid, which can cause equipment failure and power quality problems. As per this research, when MPC is implemented, the harmonic distortion is very low as compared to VC and DTC. At the slow pace of the wind, the lowest values of THD have been considered to rank the MPC at 2.7% (minimum value) at the wind speed of 14 m/s. Instead, DTC recorded the greatest THD under conditions where wind speeds gave values going over 6%. WV at VC exceeded DTC, but it was a bit lower than MPC and reached its highest point of 5 percent of wind speed reductions (Huang et al., 2016).

The ability of predictive control can be used to argue why MPC functions better in reducing THE. Since it can simulate the future of the system, it can pre-compensate the control signals so as to prevent harmonic distortion even before it sets in. It can be applied to ensure MPC is preemptively deployed by improving power quality, in systems that are sensitive to harmonic distortion as a result of grid compliance (Singh et al., 2018). Our findings align with previous research works that have established the effectiveness of MPC in reducing THD in wind energy networks and improving power quality (Gao et al., 2020).

Dynamic Response Time

The response time of a wind energy system is its critical parameter, particularly in a region where wind speed change is very rapid. The response time system is powerful because it has the ability to accommodate any change in conditions of the wind within a short time in order to ensure the performance of the generator has been maintained to a fairly high level. In this work, MPC had the fastest response times with a shortest value of 50 ms at 10 m/s and registered performance within close proximity of 50 x to 60 ms per wind value. In the meantime, VC rate responses were quicker 75 ms-85 ms, and the lowest response rates recorded at low wind speeds were in DTC, which was more than 90 ms (Zhang et al., 2019).

The discrepancy is attributed to the process that approximates the subsequent alterations in the wind turn and deviation of contingent control measures even before they occur. This kind of active control guarantees that the system reacts much faster to the dynamics variation, and it is less difficult to manage and work under the unexpected change of wind speed (Liu et al., 2018). It is backed by the literature that has demonstrated higher dynamical performance of MPC over conventional controller schemes especially in applications where the reaction time plays a significant role (Qian et al., 2017).

Fault Recovery Performance

The next performance gauge of the wind power systems is fault recovery where instead of steady conditions, voltage sag can result in outage within the grid. In the research MPC had the minimum fault recovery time and was able to recover in 90100 ms whenever there was change in voltage sag. DTC however, had the longest re-cov-er-y-times, 190 ms at low wind periods. Medium recovery VC was 130-150 ms (Xu et al., 2016).

This predictive, responsive capability of the MPC leads to this fault recovery capability of the MPC. With prior notice of anomalies, corrective measures can be established in advance by MPC through predicting anomalies before their occurrence and eliminating the effects of the mistake and accelerating the healing process by anticipating the anomaly. This is even more crucial when they are integrated into a grid system where quick removal of faults is critical in the observation that the system is stable (Jiang et al., 2019). These findings are consistent with current scientific literature stating that MPC has the benefits of being fault resistant and having the ability to develop quicker recovery percentages than the other control strategies (Xie et al., 2017).

Implications for Wind Energy Systems

The possible implication of the present research is the dire importance to poor design and efficiency of wind energy systems. Although conventional approaches such as VC and DTC have succeeded in controlling new wind generation turbines, MPC could be an excellent alternative since it provides the advantages of controlling the voltage stability of power production, harmonic distortion, fast response, and fault restoration. The dynamic flexibility, as well as the capacity to model future predictability enables MPC to operate more effectively and consistently, making it especially applicable in translating to high-capacity wind farms and offshore units, where the wind conditions can become very variable and uncertain (Jafari et al., 2020).

Further, the results of this study demonstrate that it is not just convenient use of energy but also on the quality of power to which it is provided. As the renewable energy sources are increasingly connected to the grid, reducing or removing harmonic distortion and grid compliance will become increasingly relevant. The ability of MPC to optimize THD and improve power quality is a unique benefit of mitigating these issues in order to possess wind energy systems effectively in its operation and at the same time generate excellent and consistent power output.

Conclusion

Lastly, this thesis has provided a comprehensive state of the art report of three optimised controllers VC, DTC and MPC in wind energy converting systems. These results show that the MPC outperforms both VC and DTC in all the primary performance parameters which include power output, voltage stability, THD, response time, fault recovery. The possibility of increased dynamic performance and improved grid access comes out of the predictability of MPC which looks at its future in wind energy systems. As the energy generated by wind power usage rises as a leading type of renewable energy, innovative control measures like MPC will take centre stage in providing optimal efficiency, power quality and secure systems.

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