Control Strategies for Bidirectional DC-DC Converters: An Overview

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Abstract. The energy produced by renewable energy sources has variations as these sources are sensitive to weather conditions. To overcome this problem, storage devices like batteries are used for stabilization. Bidirectional DC-DC converter is the main component to interface renewable energy sources with energy storage devices. With the help of proper switching techniques, these converters have the ability to increase or decrease the level of the voltages and can handle the power flow in both directions, from source to storage device (forward direction/charging mode), as well as from storage device to source (backward direction/discharging mode). Hence for an efficient system, the control of power flow must be very effective. This paper presents an overview of various bidirectional DC-DC converter’s classical and supervisory control methods that have been proposed in recent years.

1. Introduction

The global energy demand proliferates every year with increasing technology and fast industrial growth rates of high dense regions like South East Asia, Europe, and USA. However, the fossil fuels are in rapid extinction. On the other hand, supplying electric power with quality and reliability has been a challenge due to the overloads in the grid transmission systems. Renewable energy sources provide the ideal answer to the above questions, but the variable nature of these sources does not allow having continuous and reliable source of energy when these resources are used as sole source of power and cause unfavourable effects on the power quality of the connected grid. To overcome this issue, energy storage devices use besides renewable sources. With the use of these devices such as battery packs or super-capacitors, power fluctuations can be eliminated in order to deliver smooth power to the consumer and maximize the energy output of the renewable energy sources.

A bidirectional DC-DC converter is the key element to interface between high voltage DC buses with distributed energy storage devices and low voltage DC buses with distributed energy storage devices in micro grids as shown in figure 1. A bidirectional DC-DC can be used to step down the DC voltage level “buck- converter”, step up the DC voltage level “boost- converter” or both step down-step up converter “buck-boost converter”, and can transfer power in both directions, forward as well as backward as shown in the figure 2. In classical DC-DC converter a bidirectional characteristic can be achieved by the use of anti-parallel diode with MOSFETs or IGBTs. With the help of controlled switching methods, this configuration allows the flow of current in forward direction as well as in backward direction. Due to its bi-directional ability, it reduces the size,
improves the performance and overall conversion efficiency of the system as it does not require two different converters for forward and backward flow of power. Recently it has been getting a lot of attention in academics and vast amount of research studies have been conducted on the controlling techniques for DC-DC converters. The fundamental aim of the controlling method is to provide a fast dynamic response and must have a stable DC output voltage in both power flows (forward and backward) despite the limited amount of sensors. For better and efficient performance of the system, a high efficient bidirectional DC-DC converter is required in order to control the flow of power in both directions by using switching techniques. So an efficient control technique is important for a DC-DC converter as it has two conversion stages (Inverter stage and Rectifier stage). In this paper, an overview of different control methods for bi-directional DC-DC converters is done, and these techniques are critically compared.

![Figure 1. Micro grid with Energy storage devices](image1.png)

![Figure 2. Bidirectional flow of power](image2.png)

2. Proportional-Integral-Derivative Control
A classical PID control is the most simple and easy to implement control method. Due to its excellent control dynamics with zero steady-state error, very swift response, and higher stability, it is the first choice for designing a control algorithm. The generic block diagram of a PID controller is shown in the figure 3. In [1] a pulse width modulation (PWM) is used in conventional bidirectional DC-DC converter for generating the triggering pulses of the switches. As firing angle is fixed, so due to a small variation in input voltage, a high fluctuation in output voltage is observed. To overcome this issue PID controller is proposed. The operating principle of PID controller is discussed in [2, 3]. Despite the change in input supply voltage the output remained constant because the output voltage of the converter is compared with the desired set value, and triggering signals are given to the switches to obtain the fixed desired output voltage.
In [4] a comparison between PID and PI controllers for bidirectional DC-DC converters is discussed in terms of rise time, fall time, steady-state error, and peak overshoot. It is found; PID produced less settling time and steady-state error. During boost mode, PID controller had a settling time of 0.6 sec, and a steady-state error of 0.5 volts, whereas PI controller had a settling time and steady-state error of 0.81 sec and 0.8 volts respectively. Similarly, during buck mode, a steady-state error of 0.71 volts and 0.92 volts is observed with the PID controller and PI controller respectively. As in PI controller, oscillations and overshoot occurred in response to the output of the system. So, an additional derivative gain component with PI is used to eliminate overshoot. Similarly in [5], another comparison in terms of output voltage’s stability is made between PID and PI controllers for bidirectional converters used in electric vehicles. In case of PI control method, for different input supply voltage, less variation in output voltage is observed. So while choosing PID or PI, there is always a trade-off between output voltage stability and overshoot. Although PID controllers have high reliability, high dynamics, and are suitable for many control problems, however, they have lack of robustness in the presence of uncertainty and large disturbances. There are many applications where they have very low efficiency especially when non-linearity is present in the system.

![PID Control Diagram](image)

**Figure 3.** Block diagram of PID control

### 3. Phase Shift Control

Single-phase shift (SPS) control is a widely used control method for isolated dual active bidirectional DC-DC converters [6, 7]. In single-phase shift control method, a phase shifted square wave with a 50 percent duty ratio is generated by turning on cross-connected switches of both bridges of the dual active bidirectional converter. The voltage of the transformer’s leakage inductor (VL-T) can be varied by regulating the phase-shift ratio between V1 (bridge 1 equivalent ac output voltage) and V2 (bridge 2 equivalent output voltage). Through this voltage change, the power flow direction and its magnitude can be controlled. SPS control is very effective because of its various benefits, such as high dynamics, low inertia, and easy implementation. However, the converter cannot work under zero voltage switching (ZVS) because the flow of power and its control depend on the leakage inductance of the transformer. When there is a mismatch between the transformer’s primary and secondary voltages magnitude then it causes large circulating power that eventually increases the RMS and peak currents as shown in the figure 4(a). Hence power conversion loss becomes high and the overall efficiency of the converter is reduced.

In power transmission process, there are intervals when there is a backflow of power (negative flow) and as in a single phase shift method, the power flow depends on the leakage inductance of the transformer. So when back power flow increases, then the forward power flow also increases and results in high circulating power. To overcome this issue, an extended phase shift (EPS) is proposed. EPS is an improved method of SPS. The working principle, soft-switching property, and power losses of extended phase shift have been studied in [8-10]. In this method, the cross-connected switch pairs of one bridge are turned on, whereas the cross-connected switch pairs of the second bridge are turned on with an inner phase shift ratio. The ac output voltage of one bridge gives a three level wave and the output of second bridge becomes a two level square wave with a 50% duty ratio as shown in the figure 4(b). During zero-voltage time intervals of the bridge with three-level wave, the backflow of power is zero so the circulating power reduces. Contrast with SPS, EPS has two phase shifts, an outer phase-shift ratio (D1), which is the phase
shift between the primary and secondary voltages of high-frequency transformer and is used to control the magnitude and direction of power flow, and the inner phase-shift ratio (D2) which is used to increase the zero voltage operating range and decrease the circulating power. However in this control technique, when the power flow direction is changed between forward and backward and voltage conversions are changed between buck and boost mode, the operating states of both full bridges are needed to be exchanged in order to get the minimized circulating power. The dual-phase shift control is proposed in [11]. The working principle, soft-switching property, and power losses of dual phase shift control have been discussed in [12-15]. In contrast with EPS, the ac output voltages of both full bridges are three-level waves as in this method the cross-connected switch pairs of both full bridges are turned on with an inner phase shift with the same shift ratio as shown in figure 4(c). Because of this, the operating states of the bridges are not needed to be exchanged during power (forward to backward and vice versa) and voltage (buck to boost and vice versa) transitions. Compared to SPS method, DPS has steady-state current, increased zero voltage switching operating range, and decreased current stress. Therefore overall efficiency of the system is increased. Comparing SPS, EPS, and DPS from the view of performance in large practical applications, DPS is a relatively optimal control method because of its fast dynamic response, high efficiency, easy implementation, and ZVS operating range.

Figure 4. (a) SPS (b) EPS (c) DPS [11]

4. Sliding Mode Control
Due to the presence of non-linear elements in different topologies of bidirectional DC-DC converts, the dynamic equation of the converter becomes non-linear. One approach in designing the control algorithm of that model is to make it linear with the help of linearization methods [16]. But, this method does not represent the exact model as it is based on assumptions and estimations. So, to get a fast dynamic and reliable system that can respond to external disturbances then it is more suitable to use non-linear control method for controlling bidirectional DC-DC converters. Sliding mode is one of the widely used non-linear control method because it has fast dynamic response, robustness against variations in parameters and low sensitivity to external disturbances [17]. The generic block diagram of sliding mode control is shown in figure 5. In [18] for coupled-inductor bidirectional DC-DC converter a sliding mode control is proposed. The proposed sliding mode technique tracked the reference DC voltage of the high side with high
performance, which shows its robustness against perturbations. In [19] a sliding mode control of fixed frequency bi-directional DC-DC converter is studied. The comparison is made between PI and sliding mode control in terms of load disturbances and variation in parameters. An overshoot of 5 volts and 11 volts is observed with sliding mode control and PI controller respectively. This shows that sliding mode control is more robust, and has a very low overshoot compared to the PI controller. It is because the sliding mode of control variables is designed according to the need and has nothing to do with the system parameters and external perturbations.

Although this control technique has the robustness and dynamic response. But there are also some limitations, as correct parameters and state information are required. Furthermore, in the sliding mode control technique, there might be unwanted oscillations with finite frequency and amplitude. These undesirable oscillations are known as ‘chattering’[20]. To reduce this chattering phenomenon a fuzzy-sliding control is proposed in [20]. With the combination of these two methods, very good robustness can be achieved despite the presence of outer disturbances, and the system will also get stable as the oscillations in the system will be minimized.

![Block diagram of sliding mode control](image)

**Figure 5. Block diagram of sliding mode control**

5. **Fuzzy Logic Control**

For complex and non-linear system with load disturbance, fluctuation in parameters and uncertainty, a robust response can be achieved with the help of fuzzy logic controllers. These controllers use a very versatile set of if-then rules. Due to their adaptive property these controllers are gaining popularity in controlling bidirectional DC-DC converters. The foremost advantage of using this technique is that no previous information of the system’s parameters is needed and contrast with sliding control method, fewer measurements are needed to design the controller. A generic block diagram of fuzzy logic is shown in figure 6. Fuzzy controllers are of two basic types which are FuzzyPI control technique and FuzzyPSOPI (Fuzzy Particle Swarm Optimization Proportional Integral) control technique [21]. In [22] for coupled inductor bi-directional converter a fuzzy logic and PI controller has been designed. The model for both controllers with the voltage control mode is investigated in MATLAB Simulink, steady-state and transient response of the system examined. With the help of simulations it is observed that the fuzzy logic control method had a more stable and dynamic response and had less settling time compared to PI controller. In [21] a comparison between fuzzy logic and dual-phase shift (DPS) is examined for dual active bridge isolated bi-directional DC-DC converters. The study shows high performance results when fuzzy logic is implemented, and had less settling time of 0.32 sec during buck mode, and 0.34 sec during boost mode.

While with DPS, it was 0.53 sec, and 0.35 sec during buck and boost modes respectively. Furthermore, fuzzy logic particle swarm optimization PI control gave more efficient results than the other two logics, because of low proportional (Kp), integral (Ki) gain values with low error of 0.065% and 0.1% during buck and boost modes respectively, and less settling time of 0.3 sec and 0.31 sec during buck and boost modes respectively. However, in order to get minimized errors in fuzzy logic, expert knowledge is required in designing the control algorithm.
Figure 6. Block diagram of fuzzy logic

6. Model Predictive Control
A model predictive control is a dominant and arising algorithm used in power electronics and energy conversion systems. The above mentioned control techniques perform correction after the error occurs while the main feature of model predictive control is to predict the future behaviour of the control constraints. The block diagram of model predictive control is shown in the figure 7. Because of its very fast dynamic response, and swift reference tracking characteristic this mode has become most attractive control technique comparing with other classical techniques. Although this technique requires a high number of calculations, but with the help of fast, powerful and sophisticated microprocessors easily available today it is very simple to implement. It is used in energy management of fuel cell/battery/ super capacitor hybrid power source [23].

In [24] bidirectional DC-DC converter with model predictive control algorithm is designed, and the efficiency of the system is investigated experimentally with a 2.5kw prototype for a dual phase shift with PWM based control technique, and model predictive control technique. It is found that with Dual- phase shift technique the efficiency of the converter is 89.56% while, with model predictive control method the efficiency of the converter increased to 92.52% because model predictive method has zero phase shift and unity power factor between voltages and currents of high-frequency transformer hence decreasing the overall reactive power of the converter. In [25] a model predictive control method based on cuckoo search algorithm (CS-model predictive method) is proposed for interleaved parallel bidirectional DC- DC converters. The converter is simulated in MATLAB with the PI control method and CS-model predictive method in loading and shedding of the inductor current. It is found that CS-model predictive algorithm had a fast dynamic response with no overshoot, and a rising time of 0.86 milliseconds while PI control method had an overshoot of 6.3% with settling time of 5.02 milliseconds. One of the major problems in this method is, the non-linear behaviour of the model is locally linearized at different operating range, and in order to achieve good performance, linear dynamic design of a bidirectional DC-DC converter is needed inside this technique. To overcome this issue, the multi model predictive control method is proposed.

Figure 7. Block diagram of Model Predictive control
7. Artificial Neural Network

An artificial neural network (ANN) is a biological brain representation of a computer model and composed of thousands and millions of interconnected neuron sets bonded with weight connections to process information based on the input signals. It has a layer structure with an input layer, hidden layer, and an output layer as shown in the figure 8. In [26] ANN method is proposed for controlling bidirectional DC-DC converters used in standalone DC micro grids. On the bases of approximate dynamic programming; ANN is trained to have optimum control. From the studies, it is found that very high voltage stability of standalone dc micro grid can be maintained by using artificial neural networks. Whenever there are load changes, the output of the converter can be changed rapidly to maintain the dc bus voltages. This shows that ANN has very fast response time, very insensitive to external disturbances, and can track the reference DC voltage very rapidly.

In [27] an adaptive artificial neural network based PI (AANN-PI) is proposed for bidirectional DC-DC converters. A performance comparison is made between AANN-PI, classical PI, and sliding control in regards of oscillations, rise time and settle time. All three controllers were tested on 150 watt bidirectional DC-DC prototype under various variations in the supply input voltage. From the results it is cleared that AANN-PI controller gives better performance and has high fast dynamic response with insensitivity against external disturbances. As it is discussed, to get minimum errors in fuzzy control logic, precise expert knowledge is very important in designing a control algorithm. To overcome this limitation an Artificial Neuro-Fuzzy interference system is proposed in [28] to control the speed of brushless DC (BLDC) motor with bidirectional DC-DC converters. It is observed that despite the load variations, excellent speed control of BLDC and efficient energy conversation are achieved by combing fuzzy with neural networks. ANN can learn and model no-linear complex systems that is why it is getting very popular in modern technology era but it also has some drawbacks such as time-consuming as they need extensive training, take too much time to process large neural network, and massive amount of data is required for quality prediction.

![Figure 8. Layer structure of ANN](image)

8. Conclusion

Each control technique has its merits and demerits. Classical control methods are easy to implement and can be used for various applications but they are not effective during the presence of external disturbances. Whereas the supervisory control techniques i.e. fuzzy logic, neural networks are very suitable for non-linear systems and have a very fast dynamic response but they are complex compared to classical methods and also have some limitations. For the very fast dynamics and robustness it is recommended that use classical technique inside the closed loop of supervisory control like Fuzzy-PI or Neural-PI.
Table 1. Brief summary of control methods used in bidirectional DC-DC converters

| Control method | Control Problems | Merits | Limitations |
|----------------|------------------|--------|-------------|
| PID            | -Power flow control  
-Reduce dead time of switches[2] | -High dynamics  
-High reliability  
-Low cost[29] | -Not robust against disturbance and uncertainty  
-Low efficiency[1] |
| Single phase shift | -Power flow control  
- Minimize circulating power[30] | -High dynamics  
-zero voltage switching and soft switching control[30] | -Backflow of power  
-High inductor RMS current  
-Lack of ZVS operating range[31] |
| Extended Phase shift | -Decrease backflow of power  
-Minimize back flow of power  
-reduce circulating current[8] | -High dynamics  
-Decrease peak current  
-Increase ZVS operating range[8] | -Exchange of bridge’s operating states during power and voltage transitions[11] |
| Dual Phase shift | -Decrease backflow of power  
- Eliminate reactive power  
-reduce circulating power[30, 32] | -ZVS for whole operating range  
- High efficiency  
-High dynamics  
-Improved dead-band effect[32] | -low quality operating modes  
- Difficult to get high efficiency[21] |
| Sliding mode control | -Insensitive to external perturbations  
-Handle severe variations between load and line[31] | -Fast dynamic response  
-Reference Tracking ability  
- Robust against external disturbances and uncertainty[31] | To design model accurate parameters and state information are required[31] |
| Fuzzy control | -Minimize power consumption from grid  
-minimize control time[21] | -Fast response and robustness  
- Adaptive property  
-Applicable to inaccurate and non-linear system[21] | Expert knowledge is required[31] |
| Model predictive | -Power flow control  
-Regulation of DC voltages and currents[33, 34] | -Fast dynamic response  
- Reference tracking ability  
-predict error before it occur[35] | Limitation of using a linear model inside the algorithm[36] |
| Artificial Neural Network | -Optimal power flow control  
-model non-linear complex systems[37, 38] | -High stability  
- Fast dynamic control  
-Fast reference tracking ability[39] | - Controller need to be trained  
- Large amount of previous data required  
- Time Consuming [39] |

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References
[1] DAS R. PI CONTROLLED BI-DIRECTIONAL DC-DC CONVERTER AND HIGLY EFFICIENT BOOST CONVERTER FOR ELECTRIC VEHICLE: INTERNATIONAL ISLAMIC UNIVERSITY CHITTAGONG; 2014.
[2] Lemus J, Vélez GC, Rodriguez NJC. Pid controller design for dc motor. Contemp Eng Sci. 2018;11(99):4913-20.
[3] Khan MR, Khan AA, Ghazali U. Speed Control of DC Motor under Varying Load Using PID Controller. International Journal of Engineering (IJE). 2015;9(3):38-48.
[4] Ramya K, Jegathesan V. Comparison of pi and pid controlled bidirectional dc-dc converter systems. International Journal of Power Electronics and Drive Systems. 2016;7(1):56.
[5] Das R, UddinChowdhury MA, editors. PI controlled Bi-directional DC-DC converter (BDDDC)
and highly efficient boost converter for electric vehicles. 2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT); 2016: IEEE.

[6] Monfared KK, Iman-Eini H, Razi R, editors. Control of single-phase bidirectional pev/ev charger based on fcs-mpc method for v2g reactive power operation. 2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC); 2019: IEEE.

[7] Zhao B, Song Q, Liu W, Liu G, Zhao Y. Universal high-frequency-link characterization and practical fundamental-optimal strategy for dual-active-bridge DC-DC converter under PWM plus phase-shift control. *IEEE Trans Pow Electr.* 2015;30(12):6488-94.

[8] Zhao B, Yu Q, Sun W. Extended-phase-shift control of isolated bidirectional DC–DC converter for power distribution in microgrid. *IEEE Trans Pow Electr.* 2011;27(11):4667-80.

[9] Zheng M, Wen H, Shi H, Hu Y, Yang Y, Wang Y. Open-circuit fault diagnosis of dual active bridge DC-DC converter with extended-phase-shift control. *IEEE Access.* 2019;7:23752-65.

[10] Naayagi R, Forsyth A, Shuttleworth R, editors. Performance analysis of extended phase-shift control of DAB DC-DC converter for aerospace energy storage system. 2015 IEEE 11th International Conference on Power Electronics and Drive Systems; 2015: IEEE.

[11] Gao S, Lu X, Liu X, editors. Minimum reflux power control of bidirectional DC-DC converter based on dual phase shifting. 2018 IEEE 2nd International Electrical and Energy Conference (CIEEC); 2018: IEEE.

[12] SAVRUN MM, KOROGLU T, Adnan T, CUMA MU, BAYINDIR KC, TUMAY M. 1P3S HIGH FREQUENCY TRANSFORMER BASED DUAL-ACTIVE BRIDGE DC-DC CONVERTER. *International Journal of Energy Applications and Technologies.* 4(4):174-81.

[13] Costinett D, Maksimovic D, Zane R. Design and control for high efficiency in high step-down dual active bridge converters operating at high switching frequency. *IEEE Trans Pow Electr.* 2012;28(8):3931-40.

[14] Kim M, Rosekeit M, Sul S-K, De Doncker RW, editors. A dual-phase-shift control strategy for dual-active-bridge DC-DC converter in wide voltage range. 8th International Conference on Power Electronics-ECCE Asia; 2011: IEEE.

[15] Hong M, Xuanjie G, Chengbi Z, Shuijiang D, editors. An improved dual phase shift control strategy for dual active bridge DC-DC converter with soft switching. 2018 International Power Electronics Conference (IPEC-Niigata 2018-ECCE Asia); 2018: IEEE.

[16] Filsoof K, Lehn PW. A bidirectional multiple-input multiple-output modular multilevel DC–DC converter and its control design. *IEEE Trans Pow Electr.* 2015;31(4):2767-79.

[17] Cao J, Chen Q, Zhang L, Quan S, editors. Sliding mode control of bidirectional DC/DC converter. 2018 33rd Youth Academic Annual Conference of Chinese Association of Automation (YAC); 2018: IEEE.

[18] Ciccarelli F, Lauria D, editors. Sliding-mode control of bidirectional dc-dc converter for supercapacitor energy storage applications. SPEEDAM 2010; 2010: IEEE.

[19] Jeung Y-C, Choi I-C, Lee D-C, editors. Robust voltage control of dual active bridge DC-DC converters using sliding mode control. 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia); 2016: IEEE.

[20] Utkin V. Chattering problem. *IFAC Proceedings Volumes.* 2011;44(1):13374-9.

[21] Kayaalp RI, Demirdelen T, Tümay M, editors. A novel fuzzy logic control for bidirectional DC-DC converter and comparison with dual phase-shift control method in medium voltage applications. 2016 IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA); 2016: IEEE.

[22] Narasimharaju B, Dubey SP, Singh S, editors. Intelligent technique for improved transient and dynamic response of bidirectional DC-DC converter. 2010 International Conference on Power, Control and Embedded Systems; 2010: IEEE.

[23] Bambang RT, Rohman AS, Dronkers CJ, Ortega R, Sasongko A. Energy management of fuel cell/battery/supercapacitor hybrid power sources using model predictive control. *IEEE Transactions on Industrial Informatics.* 2014;10(4):1992-2002.
[24] Akter P, Uddin M, Mekhilef S, Tan NML, Akagi H. Model predictive control of bidirectional isolated DC–DC converter for energy conversion system. *International Journal of Electronics*. 2015;102(8):1407-27.

[25] Sun W, Chen Q, Zhang L, editors. Model Predictive Control Based On Cuckoo Search Algorithm of Interleaved Parallel Bi-directional DC-DC Converter. 2019 34rd Youth Academic Annual Conference of Chinese Association of Automation (YAC); 2019: IEEE.

[26] Li S, Fu X, Weizhen D. Systems, methods and devices for control of dc/dc converters and a standalone dc microgrid using artificial neural networks. Google Patents; 2019.

[27] Ibeas A. Artificial Neural Network Based Adaptive Control of Single Phase Dual Active Bridge with Finite Time Disturbance Compensation.

[28] Kavathe R, Chandle JO, Patil N, Kokare M. ANFIS Based Speed Control of BLDC Motor with Bidirectional DC-DC Converter. *International Journal of Research and Scientific Innovation (IJRSI)*. 2018;5(6):153-8.

[29] Knospe C. PID control. *IEEE Control Systems Magazine*. 2006;26(1):30-1.

[30] Kumar BM, Kumar A, Bhat A, Agarwal P, editors. Comparative study of dual active bridge isolated DC to DC converter with single phase shift and dual phase shift control techniques. 2017 Recent Developments in Control, Automation & Power Engineering (RDCAPE); 2017: IEEE.

[31] Gorji SA, Sahebi HG, Ektesabi M, Rad AB. Topologies and control schemes of bidirectional DC–DC power converters: an Overview. *IEEE Access*. 2019;7:117997-8019.

[32] Hou N, Song W, Wu M. Minimum-current-stress scheme of dual active bridge DC–DC converter with unified phase-shift control. *IEEE Trans Pow Electr*. 2016;31(12):8552-61.

[33] Mayne DQ. Model predictive control: Recent developments and future promise. *Automatica*. 2014;50(12):2967-86.

[34] Grüne L, Pannek J. Nonlinear model predictive control. Nonlinear Model Predictive Control: Springer; 2017. p. 45-69.

[35] Parisio A, Rikos E, Glielmo L. A model predictive control approach to microgrid operation optimization. *IEEE Transactions on Control Systems Technology*. 2014;22(5):1813-27.

[36] Batliner M, König O, Jakubek S, Prochart G. Method and controller for model predictive control of a multi-phase DC/DC converter. Google Patents; 2019.

[37] Qasim M, Khadkikar V. Application of artificial neural networks for shunt active power filter control. *IEEE Transactions on industrial informatics*. 2014;10(3):1765-74.

[38] Van Gerven M, Bohle S. Artificial neural networks as models of neural information processing. *Front Comput Neurosci*. 2017;11:114.

[39] Zulu A, John S. A review of control algorithms for autonomous quadrotors. *arXiv preprint arXiv:160202622*. 2016.