

Increased use of power electronic converters engineering essay

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An extensive literature survey is carried out in AC-DC converter using with and without PWM technologies. AC-DC converter used for applications in low-performance and high performance, the half-wave and full-wave (H-bridge) converters are used, respectively. In half-wave converter, topology has half the number of switches of the full-wave topology. The half-wave topology can deliver power only for motoring in both the directions without regenerative capability. In the full-wave converters with two controlled switches having anti-parallel diodes per phase, bidirectional flow is achieved.

2. 2 LITERATURE REVIEW

The front-end PWM converter is of great concern for researchers and industrialists due to its advantages over other systems. PWM rectifiers are extensively used in battery charger, regulated DC voltage source, UPS systems, AC line conditioner and motor drives. The research potential of the drive is especially towards development of high voltage and high power PWM converter with high performance capability for the different applications. An exhaustive literature survey is carried out in following broad areas of the PWM techniques converter. Power quality issues and harmonic analysisDesign and modelling of the front-end PWM Controlled power converter. Inner loop current controllersOuter loop voltage controllersVarious standards are set to limit the harmonics generated by use of power electronic devices and non-linear loads. IEEE standard 519 was first issued in 1991. It gave the first guidelines for system harmonics limitations and revised in 1992 [193]. The 5% voltage distortion limit was recommended below 69 kV, while the limit on current distortion is fixed in the range of 2.5% to 20% depending upon the size of the customer and the system voltage.

IEEE 519 standard limits harmonics primarily at the service entrance, while IEC 1000-3-2 [194] is applied at the terminals of end-user equipment. Active Power Filters (APFs) are seen as a vital alternative over the classical passive filters and static VAR compensators to compensate harmonics, reactive power requirement and improved power factor of nonlinear loads. APFs are also called Active Filters (AFs), Active Power Line Compensators (APLCs), Instantaneous Reactive Power Compensators (IRPCs) and Active Power Quality Conditioners (APQCs) [195]. The objectives of active filtering are to solve these problems by combining the advantages of regulated systems with much reduced rating of the necessary passive components. The APFs are generally built around a PWM converter with a capacitor/inductor on its DC side. The PWM converter switches are controlled to draw/supply a compensating current from/to the utility so that it cancels current harmonics on the AC side, by generating the nonlinearities opposite to the load nonlinearities, and makes the source current almost sinusoidal. Yeddo B. Blauth and Ivo Barbi [164] proposed a three-phase 12-pulse phase controlled rectifier with unity displacement factor, low line current harmonic content, two quadrant operation and absence of phase shifting transformer. The circuit is composed by two three-phase 6-pulse rectifiers in parallel connected by four balancing reactors. One is a conventional thyristor rectifier with a lag firing angle (α). The other is an active rectifier composed by GTOs or IGBTs and diodes, operating with a lead (and symmetrical) firing angle ($-\alpha$). The 12-pulse operation with line frequency modulation provides a 5-level line current with reduction or cancellation of certain harmonics. By using this method, unity displacement factor, high power factor, low line

current harmonic content and low switching losses are obtained with a parallel connection of two rectifiers. The proposed rectifier does not use a phase shifting transformer and it uses current multi-levels and a simple line frequency modulation strategy, instead of high frequency modulation. M. Jasinski and M. P. Kazmierkowski [114] have analyzed three-phase, bi-directional PWM converter used extensively in high power applications such as motor drives, APF and PWM rectifier. It is often required to test the converter at its rated kVA before it is used actually in applications. An electrical source of high capacity and suitable load bank are required for the load testing of such a converter, which may not be available in the development or production site. Further, a considerable amount of electrical energy in testing of the converter is added up, as proved by Huang and F. S. Pai [115, 116]. The modern drive specifications are required to meet the new IEEE-519 standard, to avoid current and voltage harmonic distortions of the utility. The new standard requires a harmonic analysis of entire power system to specify to the near correct value of variable frequency drive technology for the applications and ensure compliance with standard. The main problem is enforcing the standards. Present assumption is that voltage distortion is the responsibility of utility and current distortion is the responsibility of the user, as discussed by McGranaghan and Mülleller [63]. P. R. Keskar [68] derives a general methodology for computing voltage and current distortion in accordance with 519-1992. Due to voltage and current harmonic limitations, the VFD market is moving towards higher switching devices. The utility voltage orientations control has fast response similar to HCC. Implementation of voltage orientation control is complicated. Rusong

Wu, et al. [69] have analyzed and predicted that current control with a fixed switching frequency has a fast dynamic response, ease of control and good switching pattern. Lian and Lehn [172] have observed that single-phase full bridge rectifiers are heavily used in low voltage distribution system. It is, therefore, essential to predict the harmonic levels that these converters produce. In their paper, a fast time domain method is presented to solve for the current and voltage harmonics injected by single-phase diode bridge rectifiers. The method is highly accurate and it does not suffer from harmonic truncation errors or aliasing effects that exist in harmonic domain analyses or brute-force methods for time domain simulation. Caseiro and Mendes (2009)[204] have discussed a new power quality issues and concerns about how the electrical devices connected to the mains behave and how their behaviour affects the mains power quality and, consequently, other energy consumers. In result of these recent concerns, various new standards were made to limit the harmonic pollution that each device may produce. Diode rectifiers are one of the main polluters, not complying with these standards. The necessity for alternatives reaffirmed PWM rectifiers as a viable alternative. PWM have additional capabilities as unity power factor and energy regeneration. They comparison have done for diode and PWM rectifiers. A Matlab/Simulink model has been made to allow the comparison. PWM advantages such as low current distortion, controllable DC voltage level, controllable power factor and regenerative capabilities are demonstrated. Sinusoidal Pulse Width Modulation (SPWM) and Sinusoidal Vector Pulse Width Modulation (SVPWM) modulation strategies are compared. They demonstrate the superiority of the PWM rectifier systems

over the traditional diode ones. Several operation conditions analysed and new capacities explored showing that, although new PWM rectifiers are more expensive, they have superior features not only in energy quality terms but also in applications where diode ones could not be applied, as in energy regeneration. This may justify, in many cases, the price difference. The obtained results prove also the efficiency of the proposed control scheme and the implementability of the system. Presented results also establish SVPWM as the most efficient modulation technique have analysed.

Simulation and experimental results demonstrate the properties and capabilities of PWM rectifiers. In the Space Vector Modulation (SVM) technique, the input phase voltages are divided into six 60° intervals; within these intervals there is no sign changed. The switching is done such that the actual voltage tracks the reference voltage. Thus, SVM technique provides fast dynamic control but its implementation is complicated and complex, and requires significant computational resources. Chem-Lin Chen, et al. [70] have developed a simplified control scheme utilizing SVM to calculate the duty ratio required to synthesize the reference voltage. B. D. Min, et al. [71] have analyzed that with the SVM technique, maximum output voltage is 15.5% greater than the number of switching and is about 30% less at the same carrier frequency than that with the sinusoidal PWM method. The state vector modulation based HCC technique incorporates advantages of both the SVM and HCC techniques. It is analyzed by many researchers such as Dixon, et al. [72], Wu, et al. [78], Ooi, et al. [80], Wu, et al. [82], Habetler [83], Guo, et al. [84], Dzaou, et al. [85], Zargari and Joss [77], Balasako and Kaura [86], Verdelho and Marques [87], Fakula [88], Vilathgamuwa, et al. [89], Pan and

Chen [90] and Shieh, et al. [91], that the PWM AC/DC voltage source converter, as compared to other converters gives excellent response and is widely used. Phase controlled converter merits attention because of its ability to deliver near sinusoidal currents at unity power factor. Various control strategies have been proposed in recent work on use of PWM converter, although the same goals have been achieved through these control strategies such as high power factor, near sinusoidal current and voltage waveform and reduction in THD. Juan W. Dixon and B. T. Ooi [72] report a unity power factor sinusoidal current boost type three-phase rectifier with an indirect control method. The scheme proposed by them replaces the inner hysteresis current feedback loop by a standard PWM control. PWM control reduces the cost of current measuring transducers. An analytical model is developed by them with the dynamic power balance yielding characteristic matrix; with that the transient and stability limits can be predicted accurately. B. R. Lin, et al. [73] have developed sliding mode voltage controllers for the front-end PWM converters independent of load model and power supply variations or perturbations. Also with the sliding mode converter, the dynamics of the AC and DC sides are developed. J. F. Silva [74] has presented a sliding mode voltage controller for unity power factor three-phase PWM rectifiers and has shown it to be useful for the elimination of steady state errors. Speed of the response increases using just an extra current sensor or a current observer, and new space-vector α - β PWM modulator. Dee-W. Chung and Seung-Kinsel [75] have analyzed in detail the conduction and switching losses of a voltage fed three-phase PWM rectifier done for various schemes. Based on this result, to minimize the loss

in all ranges of phase angle of a three-phase rectifier, a novel PWM strategy has been developed by them. The proposed PWM strategy differs from the conventional space vector PWM is that one distributes non-modulated segments variably according to phase angle between voltage and input current which results in reduced switching frequency ratio and the absence of switching in the region of peak input current. The proposed strategy has limitation is that it needs more number of sensors and three voltage sensors. Hasan Kömürcügil and Osman Kurkrer [76] have developed PI controllers to control AC side currents. The PI controllers, which process the DC link voltage error to generate references for the AC currents in the stationary or rotating frames, control the output DC voltage. There are two PI current regulators in d-q frames. An improvement of this control strategy is proposed in the stationary d-q frame. The DC link voltage is subtracted from the reference voltage, and error is processed in a PI controller that determines the input current magnitude. The switching states of the converter are directly determined by this current magnitude; thus, the needs of input current transducers are eliminated. They have derived the mathematical model of the system in the continuous time domain. The system control equations are also derived in the continuous time domain, and the stability region for PI gains, which make the operating point stable, are also found. They have analyzed that there is optimal AC/DC converter in which the output is pure DC voltage (or current) and input draws a pure sinusoidal current at unity power factor from three-phase AC line. However, in practice, a converter with these requirements cannot be realized. Conventional thyristor phase-controlled converters have an inherent drawback that as the

firing angle increases, power factor of the line decreases, and that harmonics of the line current are relatively high. In recent years, there is a great tendency to operate AC/DC converters with PWM switching patterns to improve the input and output performance of the converter. J. W. Dixon and Boon-tech Ooi [72] have discussed an indirect control method of a unity power factor sinusoidal current boost type three-phase rectifier. The scheme replaces inner hysteresis current feedback loop by a standard sinusoidal PWM control, which reduces cost of current measuring transducers. With the dynamic power balance equation, an analytical model is developed yielding characteristic matrix; with that, the transient and stability limits can be predicted accurately. B. R. Lin, et al. [73] have used sliding mode voltage controllers for the front-end PWM converters that are independent of load model and power supply variations and perturbations. Also with the controller, the dynamics of the AC and DC sides are decoupled. J. Fernando Silva [74] has discussed a sliding mode voltage controller for the unity power factor, three-phase PWM rectifier and has shown it to be useful for the elimination of steady state errors, for increasing the speed of response using just an extra current sensor or a current observer, and a new space vector α - β PWM modulator. Chung and Sul [75] have analyzed in detail the conduction and switching losses of a voltage-fed three-phase PWM rectifier for various PWM schemes. Based on the result, a novel PWM strategy that minimizes the loss in all range of phase angle of a three-phase rectifier is developed. The proposed PWM strategy differs from the conventional space-vector PWM in that, the proposed one distributes non-modulated segments variably according to phase angle between voltage and input currents in reduced

switching frequency ratio and the absence of switching in the region of peak input current. The limitation of the strategy is that it needs more number of sensors, i. e. three current sensors and three voltage sensors. To control the AC side currents, the PI controllers are used by Hasan [76], Navid and GCza [144] and Fakuda, et al. [196]. The PI controller, which processes the DC link voltage error to generate references for the AC currents in the stationary or rotating frames, controls the output DC voltage. There are two PI current regulators in d-q reference frame. An improvement of this control strategy is proposed in the stationary d-q frame. The DC link voltage is subtracted from the reference voltage and the error is processed in a PI controller that determines the input current magnitude. The switching states of the converter are directly determined by this current magnitude, thus the needs of input current transducers are eliminated. Their paper gives derivation of mathematical model of the system in the continuous time domain. The system control equations are also derived in the continuous time domain, and the stability region for PI gains, which make the operating point stable, is also found. The control equations are applied to the system in discrete time, assuming that a continuous-time approximation is valid for the discrete-time system for sufficiently high switching frequencies. Between PWM converter and DC load or drive, an Aluminium electrolytic DC-link capacitor is installed as energy storage element. For high power or high voltage motor drives, the size and weight of the capacitor required is of significantly large values. The disadvantages of large and high voltage capacitors are that they are costly and less reliable. The properties of the electrolyte capacitors deteriorate gradually with time due to continuous out-gassing, thus affecting the lifetime

of the converter system. Choosing a small DC link capacitor results in large DC link voltage ripples, which causes the semiconductor switch breakdown. Since the inverter power dynamics are not considered directly in current control of the converter, with sudden change in motor speed, the DC link voltage error becomes quite large. Namho Hw, et al. [92] have proposed a new converter control scheme, which uses the inverter dynamics for controlling the converter dynamics. The inverter power dynamics is assumed as slave system, which exactly tracks the inverter dynamics. Using the storage capacitor energy as variable, a controller for the DC link voltage regulation is designed. The proposed control algorithms need a fast processor for efficient data transfer between the converter system and the inverter system. Marian P. Kazmierkowski and Luigi Malesani [93] have analysed that the inner current control loops are applied for the converter and inverter system applied for a drive control. The performance of the converter and inverter system depends on the performance of the current controller used. The basic requirements of the current controller are that (i) It should track the command current without phase and amplitude errors over required output frequency range. (ii) It should have fixed or limited switching frequency range for safe operation of semiconductor or power devices. (iii) It should have low current harmonic contents. (iv) It should provide fast dynamic response to the converter or inverter system and (v) It should make maximum utilization of the DC link voltage. The current control techniques are represented in two groups, linear control techniques and non-linear control techniques. The linear controllers operate with open loop voltage modulator like sinusoidal PWM. SVM and optimum PWM carry advantages of constant

switching frequency, well-defined harmonic spectrum, optimum switch pattern and good DC link voltage utilization. In general, the controllers are used in linear group or PI stationary state to provide feedback and are predictive with constant switching frequency. The non-linear current controller group includes hysteresis, delta modulation, on-line optimized controllers, neural network and fuzzy logic controllers. Another category of current controlled converters is soft switching resonant DC link with zero-voltage switching. In this type of controller, the commutation process is restricted to a discrete time, when the DC link voltage pulses are zero. At present, the research trend favours fully digital control with high-speed processors. The current control methods, which allow for digital implementation, are preferred even with some sacrifice in accuracy and dynamic performance. For low performance applications like pumps, blowers and fans, and retrofit applications, the digitally implemented PI regulators are adequate. The use of linear predictive and online optimized current controllers is growing fast in medium and high performance systems especially for traction and high power units. HCC in their improved version are well suited to fast, accurate conversion systems like servo drives, UPS and power filters. Two major types of PWM rectifiers are reported in the literature. These are boost type rectifiers discussed by Maksimovic and Erickson [123] and buck type rectifiers discussed by Hirachi, et al. [124] respectively. The boost rectifiers are more widely used than the buck rectifiers as they draw continuous currents from the mains, and hence, generate less EMI. Many more other relative merits and demerits are discussed by Erickson [125]. In three-phase application, a three-phase,

three-wire boost rectifier, as discussed by Chattopadhyay and Ramanarayanan [128] or a three-phase, four-wire boost rectifier produced by Lo and Chen [126] and Fraser, et al. [127] may be used as per requirement. Wang Jiuhe, Xia Peirong and Zhang Jinlong (2009)[206] have improved the properties of three-phase boost-type PWM rectifiers. To apply nonlinear control theory, to study PWM rectifiers they introduce the nonlinear control strategies of three-phase boost-type PWM rectifiers, which includes feedback linearization, passivity control based on Euler-Lagrange(EL) model and Active Disturbance Rejection Control(ADRC) strategy. Three-phase boost-type PWM rectifier has many advantages, such as sinusoidal current control and unity power factor on the AC side, and DC output voltage control on the DC side, and reversible power flow between both sides etc.. Therefore, "green transformation" of electric energy is realized by PWM rectifier. The nonlinear control strategy of PWM rectifier has advantages such as fast response and good stable performances, high power factor and low input current THD etc. According to treatise and Analysis from above, the controller (18) can transform (11) into decoupling and PWM rectifier has most dynamic and static state performances compared with other control strategies. Passivity control strategy has good dynamic and static state performances. The controller plays an important role in a PWM boost rectifier system. It executes a specific control scheme to satisfy the control objectives such as maintaining a constant output voltage across the load and drawing nearly sinusoidal currents at near unity power factor from the supply mains. A set of quantities required for a particular control scheme, such as voltages and currents to be measured. These quantities are processed by the

controller to generate the required gating pulses for the devices. A number of control techniques have been reported in the literature for the PWM rectifiers by Lo and Chen [126], Fraser, et al. [127], Lai and Smedley [129], Dai, et al. [130], Rodriguez [131], Kazmierkoski and Malesani [132] and Kim, et al. [133]. Most of them discuss PWM rectifier with an inner current control loop and an outer voltage control loop. The voltage loop maintains the DC bus voltage at its reference value despite any variations in input voltage and/or load, while the current loop forces the PWM rectifier to draw sinusoidal currents at near unity power factor from the supply mains. In three-phase application, it is preferred to implement the control in the synchronously rotating d-q reference frame, as the three-phase voltages and currents appear as stationary quantities in the Synchronous Reference Frame (SRF). Therefore, the PI controllers handle DC quantities. Further, the active and reactive components of the input currents can be processed separately in a decoupled fashion. Valadmir Blasko and Ismail Agirman [134] estimated position of line voltage essential for operation of regenerative three-phase Voltage Source Converter (VSC). The PI current regulator in d-axis of VSC current controller was modified to obtain angle error signal. The angle error signal drives the observer (similar to Phase Lock Loop (PLL)), which provides position of angle of line voltages. To achieve fast and reliable lock with utility system with minimal duration of transients, initial line voltage position was estimated by measuring amount of current change when zero-state voltage vectors were applied by the output of the inverter for defined time intervals. The method was simple and easy to implement and has proved through laboratory testing to be robust. Muhammad H.

Rashid and Ali I. Maswood [135] evaluated and analysed the three-phase AC-DC converter under unbalanced conditions. They observed that the level of unbalance plays a significant role in the converter characteristics, especially at the lower output voltage range. Analysis has been done for the angle-controlled scheme, and the effects of supply unbalances on the power factor, harmonic factor, distortion factor of input and output currents, THD of output voltages, and lower order harmonics were investigated. Transfer function approach was used to derive the relationships between input and output currents. The transfer function approach is a generalized method to investigate the converter performance under various conditions. These relationships are used to simulate the converter, and the performance of the converter is evaluated. The results are presented in terms of normalized quantities and compared with those under balanced cases. A novel Inductor Voltage Control (IVC) method is discussed by Oruganti and Palaniapan [136], which is capable of achieving near unity power factor, was proposed for buck type AC-DC PWM converters. The inductor voltages are kept within a hysteresis band about a sinusoidal template for sinusoidal input currents. It was observed that this method was much less sensitive to parameter and control variations than the Delta Modulation Control (DMC) methods. A new logic scheme is proposed, which enables these problems to be overcome. Detailed simulation and experiments have been provided by them for verification. Jun Kikuchi and Thomas A. Lipo [137] have investigated the three-phase PWM boost-buck rectifiers with power-regenerating capability. The converters under consideration are capable of both step-up and step-down, bidirectional power processing and almost unity power-factor

operation with nearly sinusoidal current. They have developed firstly, a step-by-step process for power stage derivation, then taking the Cuk-Cuk realization as an example, its operating principle and modulation scheme are described. For controller design, steady state and dynamic models are also described. In their paper, they have presented the results of circuit simulation and hardware experiments. The structure of the power circuit of a new single-stage three-phase boost type PWM rectifier system, based on an analysis of basic realization possibilities, is developed by Kolar, et al. [138]. The system proposed by them has continuous sinusoidal time behaviour of the input currents and high frequency isolation of the output voltage, which is controlled in a high dynamic manner. This system has substantially lower complexity, and it allows the realization of several isolated output circuit with minimum effort, as compared to a conventional two-stage realization. Based on the conduction states occurring within a pulse period, basic function of the new PWM rectifier system is described. Moreover, a straightforward space-vector orientation method for the system control is proposed, which ensures a systematic magnetization of the transformer. Further, it makes possible a sinusoidal control of the main phase currents in phase with the associated phase voltage. By digital simulation, theoretical considerations are verified and the stresses on the power semiconductor of the new converter system are determined. Finally, results of an experimental analysis of the system are given, and direct start-up and short-circuit protection of the converter are discussed. Pontt, et al. [139] have discussed a novel optimal modulation strategy whose objective is to reduce the THD of the input current. Six- and twelve-pulse three-level neutral point clamped PWM

rectifiers are used in order to implement modulation techniques. The results confirm the advantages of the proposed strategy such that less input current distortion and remarkable reduction of higher order harmonics as compared with Selective Harmonic Elimination (SHE) method. Yongsug Suh and Lipo [140] have proposed a new control scheme of improved transient response for the PWM AC/DC converter under generalized unbalanced operating conditions. The overall bandwidth diminishing filter/functional block for extracting positive and negative sequence components has been avoided by employing dual converter regulators in positive and negative synchronous frames. The steady state error due to 120 Hz AC signals has been reduced by employing a resonant gain path in the current regulator. They have also proposed simplified current reference calculation scheme in the regulation of instantaneous active/reactive power. This method has comparatively better transient response in compensation for generalized unbalanced operating conditions (unbalanced input supply and unbalanced input impedance) of wide range while still satisfying unity input power factor correction and ripple-free DC output voltage regulation without adding any external hardware. The proposed control system has been analysed and tuned based on the AC small signal perturbed model under unbalanced operating conditions. Simulation and experimental results confirm the proposed control method under severe unbalanced operating conditions. Danielroiu, et al. [141] have proposed a new stationary frame control scheme for three-phase PWM rectifiers operating under unbalanced voltage dips conditions. The proposed control scheme regulates the instantaneous active power at the converter poles to minimize the harmonics of the input currents and the output voltage

ripple. They have developed a new current reference generator implemented directly in stationary reference frame. This allows using Proportional Sinusoidal Signal Integrator (P-SSI) controllers for simulation compensation of both positive and negative current sequence components. No Phase-Locked Loop (PLL) strategy and coordinate transformations are needed for the proposed current-reference generator. Experimental results are presented for a 20-kVA AC/DC converter proto types demonstrate the effectiveness of the proposed control scheme. A comparison with two other existing control techniques is also performed. Fast dynamic performance with small DC link voltage ripple and input sinusoidal currents are obtained with this control scheme, even under severe voltage dips operating conditions. Kaboli, et al. [142] have proposed a Random PWM (RPWM) technique applied in order to spread the noise spectrum over a wide range, thus considerably reducing the amplitudes of these harmonics and the consequent EMI problems. For the operation of the active filters, the case of an AC/DC converter along with a power factor corrector is considered as a non-linear load and a series active filter, respectively. A line-impedance stabilization network is used to study the RF noise emanating from the converter. A noise model to study the EMI emission is presented and used. Theoretical analysis of the RF noise power spectrum is carried out in order to demonstrate the advantages of the RPWM technique over conventional PWM. Experimental results confirm the validity of the theoretical calculation and simulation results, and demonstrate the effectiveness of applying the RPWM technique in reducing the RF noise level. Barbi, Ivo and Batista, Flabio Alberto Bardemaker (2010)[203] have presented the concepts for application

of SVM to two-level unidirectional PWM rectifiers, and a methodology for the use of this modulation is proposed and applied in three different groups of rectifiers. For each group of rectifiers, the converter switching stages are analyzed to determine switch control signals for SVM. One switching sequence is proposed for all rectifiers in order to minimize the number of switch commutations and reduce the switching losses. Duty cycle functions are determined, and the desired switching sequences are performed by a simple PWM. The presented application methodology for this modulation technique is based on subsector definition, rectifier operation stage analysis, and duty cycle determination. With this methodology, it is not necessary to determine the sectors of vectors, but only the desired current sectors be imposed from the input voltage references. The proposed modulation reduces the number of switch commutations and improves the rectifier efficiency. The simulation and experimental results validated the proposed modulation, and the unidirectional rectifiers offer regulated output voltage, high efficiency, improved power factor, and low input current THD. In Y-connected rectifiers, the number of switches turned on to perform the desired vectors is greater than in the other rectifiers. Δ -connected rectifiers and bridge-connected rectifiers allow the possibility to maintain one switch open for an interval of 60°. Therefore, conduction losses and switching losses are reduced in these topologies. Veas, et al. [143] have developed PWM voltage source rectifier controlled by the load DC current instead of the DC voltage. The rectifier has shown very fast dynamic response and stability characteristics, which are independent of the size of the DC capacitor. The developed rectifier's main characteristics are: a) There is neither input

current sensor nor DC voltage sensor. b) It works with an unchangeable and predefined PWM pattern. c) It presents a very strong stability. d) Its stability does not depend on the size of the DC capacitor. e) It can work at leading power factor for all load conditions, and f) It can also work with zero regulation for all load conditions. Digital computer simulations, analyses, and hardware experiments confirm all these characteristics of the control method. Zargari and Jobs [144] have proposed a current-controlled PWM rectifier as an alternative, since the straightforward power angle control of the rectifier is characterized by a slow response, and it has potential stability problems. Current control PWM rectifier provides near sinusoidal input currents with unity power factor and a low output voltage ripple. Moreover, it produces a well-defined input current harmonic spectrum, exhibits fast transient response to load voltage variations, and is capable of regenerative operation. PWM pattern generation is based on a carrier technique, and the current controller is implemented in the stationary (abc) frame and rotating (dq0) frame. The design and the performance of the two controller options are investigated and compared. A carrier comparison type current-control technique produces the switching pattern for instantaneous control and wave shaping of the input currents. The control technique operates with fixed switching frequency and has a fast response to system transients. The current controller is presented in both stationary and rotating frames. The performance and design considerations of the two controller options are compared. It is concluded that the rotating frame controller has zero steady-state error, hence very good steady-state accuracy. The transformation of AC quantities to the dq0 frame is found to be a very useful tool in evaluation

of the controller designs. A complete analysis of the overall system with design equations for control circuits is given. The theoretical results obtained are verified through simulation. Barrass and Cade [145] describe a control method, which allows a standard AC motor drive to be used as a PWM rectifier without additional hardware. Direct sensing of the supply voltages is normally required to maintain synchronisation between the input current and the supply voltage. However, the method presented only requires measurement of the converter phase currents and the DC link voltage, and not the converter terminal voltages, which are not usually available in a standard drive. By using the PWM modulator output voltage to give indirect supply-voltage sensing, phase information is available at every sample, which when used with a PLL gives robust line synchronisation. Pre-start tests, required to pre-load various parts of the control system when starting, have been described and demonstrated to give excellent supply synchronisation. Stable operation with correct line synchronisation has been demonstrated with fast load changes, DC bus overload, and severe line voltage notching. Therefore, a voltage source PWM converter can be used as the input stage to a four-quadrant variable-speed drive to give bidirectional power flow, and sinusoidal input currents with near unity power factor. Salo and Tuusa [146] discussed the control of the current source PWM rectifier in the synchronously rotating reference frame. A control system is presented in which the active and reactive powers are independently controlled with real and imaginary axis components of the supply current vector. A new damping method for supply current oscillations is introduced. The method operates in an open-loop manner and is very suitable for microcontroller implementation

since the calculated power demand is low. Furthermore, it is shown that in the synchronously rotating coordinates, where the sinusoidal variables appear as DC quantities, the compensation of the reactive power drawn by the supply filter can be done very easily. The proposed control methods are realized using a single-chip Motorola MC68HC916Y1 microcontroller. The experimental tests show excellent performance in both steady state and transient conditions. Bilgin, et al. [147] describe the application of a single-stage unity-power-factor buck-type PWM rectifier to medium- and high-power variable-speed DC motor drives. The advantages of the developed system are low harmonic distortion in AC supply currents (complying with IEEE Std 519 and IEC 555), nearly unity power factor over a wide operating shaft speed range, and nearly level armature current and voltage waveforms. Their paper deals with the design and implementation of a three-phase buck-type PWM rectifier for medium/high-power DC motor drive applications. Design criteria, important features of the resulting DC motor drives, and operating characteristics of the buck-type PWM rectifier in variable-speed DC motor applications are discussed. These properties of output voltage and current quantities of the converter eliminate entirely any failure risk in current commutation even for oldest motor designs, and further motor problems such as accelerated aging in motor insulation, and mechanical failure due to circulating bearing currents. The design criteria and operating features and characteristics of the buck-type PWM rectifier employed in a unity-power-factor DC motor drive are discussed. The performance of the resulting system has been tested on 25–65-kW 100–150-A 10–20-kHz DC motor drives, used in various processes of an iron and steel plant. Liu and

Chang [148] presented a single-stage soft-switching AC-DC converter for universal line applications. The proposed input-current shaping scheme is intentionally arranged to be charged in the duty-off time. With this design, the switch current stress in the duty-on time is significantly reduced. Meanwhile, this design produces AC modulation effect on the charging time of the boost inductor so that the input I-V curve drawn by the proposed converter has nearly linear relationship. Moreover, an active-clamp flyback-forward topology is used as the downstream DC-DC cell to alleviate voltage stress across the bulk capacitor. By deactivating the flyback subconverter and keeping the forward subconverter supplying the output power at light-load condition, the bulk capacitor voltage can be alleviated effectively and can be guaranteed below 450 V in wide ranges of output load and line input (90–265 Vrms). A three-phase four-wire system is presented by Lo and Chen [104], Fraser, et al. [105], Maksimovic, et al. [106] and Stan [107] assuming that at the PCC, input phase voltages are balanced. However, the input voltages could be unbalanced (both in amplitude and in phase) due to uneven distribution of various loads connected to the three-phase four-wire distribution network. With the unbalanced input voltages, the important issues associated are that the unbalanced and distributed input currents, neutral current (in case of three-phase, four-wire rectifier) and increase of output voltage ripple were explained by Chattopadhyaya and Zhang [112], Zhang et al. [113]. New controller design method is developed by Griorios, et al. [149] for the control of separately excited DC motors, fed by a three-phase PWM AC-DC converter. A complete model is developed using the d-q reference frame for the AC part and the conventional DC formulation for the

motor. Based on passivity analysis, by using as storage function the total energy of the system, it is proven that the system is always passive independent from the way the converter is regulated. Therefore, suitable PI controllers are proposed that achieve angular speed regulation and unity power-factor operation. They analyze a complete power system that includes a PWM AC-DC converter that feeds the armature voltage of a separately excited DC-motor. Analysis has been done to handle the AC system at the d-q axes reference frame, use of the d-q model of the PWM AC-DC converter and then combine this model with the well-known model of the separately excited DC-motor. Thus, a 5th order dynamic system results with regulated parameters the d- and q-axis components of the PWM switching duty ratio. It is proved that this system is always a passive system, independent from the way the switching duty ratio can be regulated. Therefore, they have proposed an efficient control scheme that simultaneously achieves both, speed regulation and operation with unity power factor. It is clear that this control scheme maintains the compliance property of the three-phase PWM converter and the DC motor system. Couples of PI controllers are proposed in order to regulate the angular speed of a DC motor and to achieve operation with unity power factor. Bin Su, et al. [117] have proposed an interleaved totem-pole boost bridgeless rectifier with reduced reverse-recovery problems for Power Factor Correction (PFC). The converter proposed by them consists of two interleaved and inter-coupled totem pole boost bridgeless converter cells. The two cells operate in phase shift mode. This keeps input current continuous with low ripple. In the case of individual cells, they operate alternatively in Discontinuous Current Mode (DCM) and the maximum duty

ratio is 50%, which allows shifting the diode current with low di/dt rate to achieve Zero Current Switching (ZCS) off. In the MOSFET, Zero Voltage Switching (ZVS) is achieved under low line input. The Common Mode (CM) noise interference is rather low. Thus, in brief, the conduction losses are reduced, reverse recovery process is improved, and high efficiency is achieved. Dylan Dah, et al. [118] have proposed a dual-loop peak current mode controller to achieve PFC and ensure independent bus voltage and output voltage regulations unlike single-stage AC/DC converters with uncontrolled intermediate bus voltage, a new stage AC/DC converter achieving PFC, intermediate bus voltage output regulation, and output voltage regulation, and output voltage regulation is proposed. The single power stage circuit is formed by integrating a boost PFC converter with a two-switch clamped forward converter. In this, current stress in main power switches is reduced due to separated conduction period of the two source currents flowing through the power switch. A neural network based self-tuning PI controller design method is proposed by Wang, et al. [200] to increase the robustness of the conventional fixed-gain PI control scheme. First, a neural network based friction model is suggested. Based on the frictional model, a neural-network-based self-tuning PI control system to overcome the robustness problem of the fixed-gain PI-type controller is developed. The neural-network based controller is trained first, and the trained neural network is used as dynamic PI gain supplier suitable for the drive operating conditions. Chiricozzi, et al. [95] have discussed and implemented a new gain self-tuning method for PI controller based on a fuzzy inference mechanism. The online gain self-tuning uses either step-

based or cycle-based tuning. In step-based tuning, the information such as error, derivative of error, the sum of the precedent errors, etc. from each sampling step is used to tune the gains accordingly. In cycle-based gain tuning method, with use of the information such as overshoot, rising time, etc. from each step reference changes; the gains are tuned to improve the performance. Their paper uses the cycle information for the FPI gain self-tuning. The fuzzy self-tuning PI controller incorporates adaptive ability, which yields very high performance in different varying working conditions. Cheng, et al. [150] have proposed a control strategy of an adaptive B-spline neural network for three-phase AC/DC voltage source converters, which realises a sinusoidal AC input current and unity power factor. Compared with other PWM techniques, neural network control provides an excellent component of a nonlinear system and is adaptive enough to fit the environment change. An online B-spline neural network is used because of its local weight updating characteristic, which has the advantages of fast convergence speed and low computation complexity. This is very important for real-time control applications. Both simulation and experimental results are presented to verify the effectiveness of the proposed control strategy. Bhat and Agarwal [151] have dealt with a neural-network-based SVM that gives excellent performance of the converter in terms of power quality at both input and output side of the converter. The turn-on times are generated by the Artificial Neural Network (ANN) and then converted to pulse widths through a simple logic circuit. The ANN significantly reduces the computational efforts of the modulation technique and makes the implementation of SVM algorithm very fast without losing precision compared to the conventional

SVM algorithm implementation using look-up table. The other advantages of ANN implementation are higher pulse resolution and reduced computational burden of the Digital Signal Processor (DSP). In practice, the use of DSP can be avoided and simple logic circuits can be used for the generation of PWM pulses. A comparative analysis of the converter using SVM without and with ANN implementation is also discussed to validate the usefulness of the ANN implementation of SVM. It has been observed that the ANN implementation of the SVM algorithm not only results in faster implementation of the algorithm and reduced computational burden on DSP but also better performance of the converter in terms of input power quality than that of SVM algorithm implementation without ANN technique. Wang, et al. [95] have proposed PI controller based on fuzzy inference mechanism and implemented a new gain self-tuning method. The online gain self-tuning uses either step-based or-cycle based tuning. In step-based tuning, the information such as error, derivatives of error, the sum of the precedent error, etc. from each sampling step is used to tune the gain accordingly. In cycle-based gain tuning method, with use of the information such as overshoot, rising time etc. from step reference changes, the gain are tuned to improve the performance. Their paper uses the cycle information for the fuzzy self-tuning PI controller incorporating adaptive ability, which yields very high performance in varying working conditions. FPI control strategy is most popular among various fuzzy logic controls. The control method generates incremental control output using error and derivative of error as input variables. Various methods are developed to derive the fuzzy rules and membership functions, as discussed by Joshi and Malhortra [96], Lee [97],

Klir [98], Zedeh [99] and Raviraj [100]. The performance of the fuzzy PI control system much depends on the choice of input and output scale factors. Yang, et al. (2009) [205] have proposed a control strategy for a rectifier with variable speed direct driven permanent magnet synchronous generator. In order to achieve Maximum Power Point Tracking (MPPT) for wind power generation systems, the rotating speed of wind turbines should be adjusted in the real time according to wind speeds. The fuzzy logic controller is used to track generator speed with varying wind speed to optimize turbine aerodynamic efficiency in the outer speed loop. The voltage space vector PWM in field-oriented control is adopted in the control of the generator side converter. By means of the field-oriented control, the highest efficiency of wind turbine can be reached. The wind turbine is controlled to work at optimal tip speed ratio and to capture maximum wind energy. The anti-windup controller of inner current loop is used instead of the traditional PI controller to improve the performances of current loop. Both simulation and experiments have been conducted to validate the performance of the proposed MPPT strategy, and all results have verified the effectiveness of the MPPT strategy. The integral state is separately controlled, corresponding to whether the PI controller output is saturated or not. The anti-windup PI controller can improve the dynamic performance of the inner current loop. They have investigation, a FLC based on Pre-Compensated Proportional-Integral (FPPI) speed controller is implemented for speed control of permanent. magnet synchronous generator. When a current control scheme is employed in the inner feedback loop, the FLC speed controller generates a current command. The current and speed signals are fed back to the closed

loop controller. The controller algorithm is implemented using TMS320F28335 DSP. They presented a novel control strategy of rectifier used to direct driven permanent magnet wind power system. The DC-link voltage is kept constant by using rotor speed control of Permanent Magnet Synchronous Generator (PMSG). The proposed system not only has been performed by Matlab/Simulink but also has been implemented in a real-time application. Simulation and experiment results show that the controllers have very good dynamic and steady state performance. Experimental results confirm the feasibility of the proposed method. The wind turbine is controlled to work at optimal tip speed ratio and to capture maximum wind energy. Both this novel anti-windup PI controller and fuzzy logic control method has more superior characteristic comparing with the traditional PI controller.