Three-Phase Rectifier Control Techniques: A Comprehensive Literature Survey

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Abstract: Any conventional three phase rectifier performs ac to dc rectification which has semiconductor switches to rectify and control output dc voltage. Several application domains do exist to use these rectifiers namely communication, power electronics and electrical machine drives due to its high power factor and permissible harmonic components at output. Thus, several researches are carried out over recent decade to control the 3 phase rectifiers. This paper reviews several existing controlling techniques of rectifiers to identify effective strategies to improve the performance of rectifiers. Controlling methods of the three phase rectifiers meant to improve power factor and power regulation, to reduce voltage variations and harmonics under unbalanced voltage conditions. Further, those methods must attempt to use reduced hardware and computational burden. Also the present development using pulse width modulation (PWM) and space vector PWM (SVPMM) based controls yet show the better enhancement of power factor, reduction of harmonics and other characteristics of 3 phase rectifiers, other techniques using namely PI, fuzzy PI, neural nets combined are to investigated in order to find the possibility of any improvement.

Index Terms: Power factor, Harmonics, PWM, three phase rectifier, PI controller, Fuzzy PI controller.

1. INTRODUCTION

AC-DC rectification is employed in several applications namely industrial power supplies and drives, electronic ballast, household appliances and chargers. The converters of AC-DC are categorized on the basis of commutating frequency. Diodes are commonly employed devices in rectification of AC. This converter belongs to the group of line switching type. Further, in recent days, the rectifier of thyristor or controlled power-diode based is commonly to obtain dc from ac source. This rectifier is generally easy, durable and in expensive, however it can be utilized just to obtain unipolar voltage. Moreover, it introduces the lower order harmonic components to the application that are difficult for removing. So, passive and active filters are used to eliminate these effects.

Passive rectifiers usually employ capacitors for smoothing the ripples at output as dc voltage. The process of charging and discharging by the capacitors produces spike current at the input. Such currents expose the lower order harmonics existence while on harmonic study. The presence of harmonics finds to have significant impact in the performance of electrical system [1]. The fundamental process in reducing harmonics is the pulse rectifier of multi-pulse using phase changing transformer. Alternatively, the technique will be using of passive filter to minimize the harmonic components. Further, in enhancing the power factor at input, passive filter types will be employed in filtering such harmonics. However this results the system very bulkier and costlier. On other hand, the usage of active filters contributes an excellent solution to solve this problem. By means of recent advancements of power electronic devices and configurations of converters, the generation of reactive power and harmonic components is minimized. Such converter types can also be used to correct Power Factor [2]. The input current form is managed using active type to mitigate harmonic components and to attain almost unity power factor. Several Power Factor Correction (PFC) so exists namely boost converter and Vienna rectifier, however these types cannot be utilized regenerative use. Thus for several uses of power regeneration, the PWM and SVPWM rectifiers are used as a bipolar power converter. Recently these rectifiers were identified as alternative ways to address such problems [3].

PWM and SVPWM type rectifiers got numerous merits namely low line current total harmonic distortion (THD), flow of bipolar power capacity, approximate unity power factor and improved dc coupled voltage with the reduced size of filtering capacitor. Additionally, this forms best choice for uses namely in adjusting speed control and distributing generated power due to its regeneration modus operandi[2], [4], [6].

2 CONCEPT OF CONTROLLED RECTIFIERS

Controlled rectifier is a regeneration type converter and this operates on the concept of force shifting methods. The output of this converter is a dc voltage and it must be maintained constant since dc voltage is utilized for various uses. The in variable dc voltage is attained by utilizing a capacitor with control feedback. The basic block of controlled rectifier [5] is depicted in Fig1. The operational concept of this rectifier type is to maintain constant dc voltage across connected capacitor near to the load and this is attained through feedback loop of output voltage as depicted in Fig 1. V_ref is the reference

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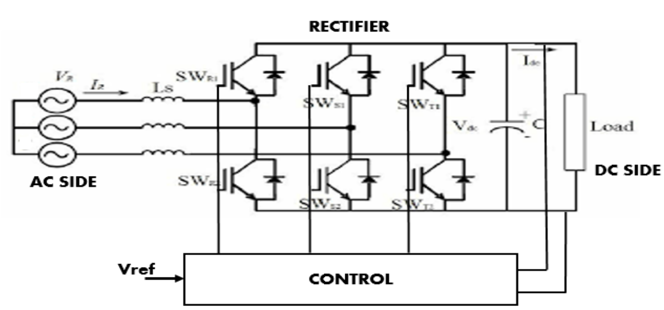

***Fig. 1**. The block diagram of controlled three phase rectifiers.*

voltage provided to the control feedback loop and will obstruct the diode conduction thereby the rectifier operates nearly with unity power factor else it operates like a three-phase bridge rectifier [6]. Comparison is performed with output dc voltage and fixed reference voltage whether the requirement is attained. The converter commutating patterns a regenerated by diverse controlling procedures [7-9]. These methods will generate pulses based on error on signal produced by the comparator. Thus the current will go back to input through coupling dc voltage. The comparator will compare the measured voltage value with set reference voltage value and when the comparator error signal is positive subsequently the capacitor that coupled to output dc discharges and hence the converter will do rectifier performance. The dc current I_0 is positive here. The controlling unit wills produce 6 pulses for every connected power devices under this condition. It too provides suitable phase difference and thus the power passes from changing input ac to output constant dc and the voltage across capacitor is recovered. On the other hand, if the output dc current happens to be negative, the capacitor gets charged surplus and this is contrasted with set reference value of voltage. Then the controlling unit manages the capacitor discharge and controls ac. The desired output voltage in rectifiers is controlled by managing the commutating pulse width. Where a sin vector controls rectifiers [10-14] every values are changed into synchronous d-q reference frame [15-23]. In this frame, these quantities are time unrelated and constant naturally, thus a step varying perturbation can be employed. But in a-b-c reference frame, every control quantities are varying with respect to time. Thus this type of control is more complex.

3 LITERATURE SURVEY WITH CONTROLLING TECHNIQUES OF THREE PHASE RECTIFIER

Hu Ma et al [24] considered a 3-phase 3-level Vienna rectifier and combined a predictive control algorithm. They proposed a synthesized algorithm of enhanced sliding mode varying system control and direct power control deadbeat prediction. The control algorithm adopted a predictive direct power regulation method. He Li et al [25] suggested a technique of Decoupled Double Synchronous Reference Frame Phase-Locked Loop (DDSRF-PLL). The transformation of grid voltage on positive and negative reference was performed, and the de-coupling network was designed to split fundamental positive and negative series elements, and the effect of cross-coupling 2ω harmonics is effectually mitigated. Further, the harmonic influence was removed by using Low Pass Filter (LPF), the grid voltage fundamental components positive and negative series elements were precisely sealed. Cheng and Huang [26] identified the problems of voltage oscillation at neutral point and zero-crossing deformity on 3φ current in Vienna rectifier. A less midpoint voltage oscillation and less deformity at zero current were designed for greater operation of Vienna filter. The balancing voltage at midpoint was attained by fine tuning of positive and negative operational period through less valued vector. A five and seven segment combinational vector combination technique was applied to mitigate the 3φ zero cross distortion on currents. For simplifying the control operation, the target vector was initially turned into as a large area, next the 3 level space vector plane was transformed into a 2 level space vector plane, and finally the modulation of SVPWM was carried out on the 3 level space vector plane. Meng et al [27] attempted to minimize the multi-pulse rectifier size by proposing a 12-pulse rectifier using power electronic phase-shifting transformer (PEPT). The frequency of ac power voltage was changed into a voltage of high frequency through power electronic converter. The voltage of high frequency was subsequently phase altered using high frequency phase altering transformer and applied as input of paired 3φ bridge rectifiers to accomplish the rectification operation. They derived the mathematical equations for the load voltage and the input current once studying the PEPT operation and 3φ diode bridge rectifier operational modes. Cheng et al [28] suggested a hybrid control method for 3φ Y connected multi-level bridgeless rectifiers (TMBR) and operation with unbalanced input voltages was discussed on the basis of expressions of TMBR structure, by focusing on mitigation of power variation through balancing dc voltages of linked capacitor and elimination of zero crossing distortion at input current. With the hybrid control scheme, the power variation was mitigated and 3φ input currents allowed to pass with a pure sine wave, apart from that, 3φ voltages of dc couple capacitor were managed to be uniform under imbalanced condition of input voltages. Additionally, hybrid control method was appropriate for every 3φ- 3-wire multi-level unipolar rectifiers under imbalanced input voltages. X.Li et al [29] aimed to minimize the grid current total harmonic distortion (THD) and output power variations under imbalanced voltages condition of grid and thus suggested a model predictive direct current control (MPDCC) method for 3 level T-type rectifier. The reference current was utilized to control goal function and evaluated grid voltages and their $1/4^{th}$ delayed values. They compared the momentary active and reactive powers positive and negative series, phase-locked loop (PLL), PWM modulation and the prevention of inner current in the loop with the usual techniques. Moreover, they selected the redundant small vectors of P and N types to control balancing neutral point balance together. Tlili et al [30] introduced a sophisticated commutation table to provide control by direct power of 3 φ PWM rectifier. This novel commutating look-up table indeed was obtained from the investigation instant active and reactive power variations. The control system objective was to keep the voltage of dc bus to a desired quantity and derive a unity power factor performance. The application of their novel commutating look-up table comprised many benefits namely a line current with an absolute sine wave and then a lower THD against common commutating table. Moreover, a power factor with unity permits to eliminate the injection cost of reactive power for compensation. They showed that the suggested method surpassed in the responses of steady state and dynamic with lesser ripples, no error while steady state response and superior dynamic perturbation rejection properties compared against traditional DPC. H. Li et al [31] proposed a new method of model predictive direct power control (MPDPC). In the conventional MPDPC, the momentary active and reactive power were concurrently managed as a particular target function, which comprised the errors of active and reactive powers. When any of the two error types got huge fluctuation, the weight for control that was focused one-sided would generate mutual interference. For solving this effect, they proposed a method of control strategy by rearranging the particular target function by including weight factors to both error types. In addition, the weight factors were derived using modulator of fuzzy logic based, which operated on the basis of positive quantity of errors of active and reactive power compared to the conventional MPDPC, The suggested control method was realized the delinking control of the active and reactive powers. Pavlova and Grigorri [32] suggested a rectifier act as voltage source that operated by keeping the dc link voltage to a set reference value with feedback control unit. They achieved this by measuring DC circuit voltage and compared with a voltage reference value. The error value was utilized to commutate the six power devices present in rectifier. If an active rectifier began to operate like rectifier, the capacitor charge would be released and the error term would signify to the control block on the power requirement from the ac supply. The control block acquired source power in generation of respective PWM signal to the six power devices. Hence, the amount of the current passes between the source and the load rises, and the capacitor voltage value is determined. Contrarily, if operate in an inverter fashion, the capacitor would be accumulate charge and error term would be enabling the capacitor to discharge with control signal and turn back power to ac mains. Feng et al [33] identified that 3 φ pulse width modulation rectifiers had issues of distortion on input current and ripple on output voltage under imbalanced voltage in the grid. The stationary frame controlling technique strategy was used to minimize the lower harmonics on input current and ripples on output voltage under imbalanced voltage drop situations of 3 φ PWM rectifier. But, its error on current might produce high harmonic components on input current. An enhanced controlling method of the current loop was suggested to further minimize the presence of harmonics on input current. The current loop used an enhanced dual-vector founded model predictive control of the current with time-delay offset, which could effectually diminish the harmonics present in the input current. Jia et al [34] designed the controller for 3 φ buck-class SWISS rectifiers. As previous models were constructed with less precision. So, they introduced the fuzzy based PI control and contrasted with the conventional PI controlling technique. Firstly they analyzed the PFC circuit operational concept of the buck-class SWISS rectifier. Subsequently the controlling scheme and the designing procedure of the model were made. Further they introduced conventional PI double closed loop control unit and the fuzzy rule of PI control, and performed the simulation finally. Additionally, they discovered that the static and dynamic behavior of fuzzy based PI controller is superior comparing conventional PI control. Ma et al [35] presented a novel system of model predictive for controlling direct power (MP-DPC) to address the disadvantages of model predictive control (MPC) for 1φ 3 level rectifiers for railway traction drives, comprising heavier on-line computation, inadequate precision in power control precision at lower commutating and changing commutating frequency. They adopted a precise mathematical expression for instant power calculation to anticipate active and reactive powers in subsequent duty period for attaining the deadbeat control and minimizing the predictive error at lower commutating frequency , lesser than 1kHz. The optimum components of d and q of voltage at input during subsequent next duty period of the assumed rectifier in rotational co-ordinate system were straightaway computed through minimization of objective function. The optimum drive pulses were produced by PWM from suggested MP-DPC except computing objective function for every voltage vector in conventional MP-DPC. Lastly they have shown that the inductance disparity impact on control system and an inductance evaluation technique enhanced the accuracy of control. Wu et al [36] proposed 3 port three-phase rectifiers (TPTPRs) by inducting a novel low voltage dc power terminal into the 3φ 6 switch boost rectifier. They provided an ac input, a low voltage dc load and a high voltage dc bus ports together in TPTPRs. A dc load voltage which was lesser comparing with the maximum amplitude of the voltage of ac line and that changes over a broad range, were connected directly to low voltage dc load of the TPTPR. They proposed an improved SVPWM method for TPTPR to achieve the regulations on voltage and current, on the basis of which section of the input ac power could be straightaway applied to the low voltage dc load during particular power transition level. Therefore, the specification of power and losses of the downlink DC-DC converter, which was linked to a high voltage DC bus port, were reduced significantly. Gui et al [37] proposed a voltage modulating DPC for 3φPWM rectifier. The differential equations explaining the dynamics of the rectifier were converted from a linear time variant into a linear time invariant system. A traditional feedback and feed-forward controlling method were suitable for the autonomous active and reactive powers control. The suggested technique also ensured that a closed model is universally exponentially steady. They used a feedback linearization technique in generation of reference for active power of interior feedbacks. Rocha et al [38] used Voltage-oriented vector control (VOC) by applying PI controllers for 3φ PWM rectifiers, because of its comparatively easier for realization. But, such controllers introduced fluctuating dc voltage for imbalanced voltage at input and harmonic components in the current because of commutation of the AC-DC converter. Their research introduced a controlling technique for 3φ impelled by sine wave based PWM in the stationary reference structure with proportional resonance controls in the inner current loop. Such controlling method presented higher dynamic operation, easier realization, reduction of harmonic components that produced by converter commutation and decrease of ripples at coupled dc voltage, because of elimination of decoupling variable. They showed a superior operation with suggested technique through reduction in ripples of coupled dc voltage and THD of the grid current and faster momentary response for power fluctuations. Fekik et al [39] designed an intelligent method for Direct Power Control method to PWM rectifier. This controlling method enhanced the PWM converter operation, termed as Artificial Neural Network (ANN) based Direct Power Control, used for selecting optimum control vector. ANN based DPC guaranteed soft control over active and reactive power in every part and decreased the ripples in current. Lastly, they tested designed DPC through simulation and proved that the outcomes of the suggested DPC method were superior in operation. Li et al [40] proposed a hybrid control method using dual loops for 3φ Vienna rectifier. PI controller was developed for external loop to control the coupled dc voltage and reactive power at input. Finite set based model predictive control (FS-MPC) was adopted for interior loop to regulate the currents at input and hold the voltage balance at neutral point. A broad state observer was presented to evaluate the current in load in order to decrease cost. They have shown that their suggested control method bear certain merits on operation, reactive power capacity at input with broad functioning scope, computing task and omission of modulation technique. Nikitin [41] introduced a basic analog technique with less complex digital realization to regulate 3 φ 6 switch bi-directional boost rectifiers with higher quality on power. His designed controller, possibly termed as Inductor Current Mapping (ICM), comprehensively integrates pliant control choices, EMI, start-up, and overload control, uncontrolled frequency operability, and endurance to imbalance of mains voltage imbalance and phase losses. Their method further provided a simple load distribution with N + 1 redundancy, and contributed several means for optimization of the cost function with size, weight and performance tradeoff. Menzi et al [42] introduced a novel phase-modular bidirectional 3φ boost-buck AC/DC converter structure. They designed every 3φ units to operate separately and comprised a boost-buck converter, permitting to straightaway modify an input ac voltage into an absolute output dc voltage just by modulating anyone of the converter from two at an instant, where the input ac voltage is used in comparison with common point to whole phases. Thus, a single level high frequency energy changeover was activated, following in an extremely dense and effectual implementation of converter system. They obtained the fundamental design of the phase modular converter (PMC) using popular cascade structure of a 3φ boost-class rectifier and following DC/DC buck converter. Moreover, the respective output dc voltage control method was introduced which permitted a stable changeover between boost and buck performance for every phase. Lastly, they compared the proposed phase modular converter with traditional two stage system through basic indices including a 2D Pareto optimization regarding power density and efficiency. Xie e al [43] discussed that Vienna rectifier was a customary 3 level rectifier using complex working constraints. And these constraints caused a design problem in controller having superior dynamic operation. So they proposed a model predictive control with optimum switching sequence (OSS-MPC) method for 3φ Vienna rectifier with the belief that the predictive control is superior in handling the constraints. A PI controller was developed to control the coupled dc voltage. An enhanced OSS-MPC technique was used to regulate the currents at input. Further, they contrasted proposed and traditional finite control set based model predictive control and stated that the proposed got enhanced steady state operation, stable commutating frequency, and avoidance of weight factors. Hadjeras et al [44] proposed a hybrid control rule for the 3φ 3 level Neutral Point Clamped (NPC) converter operating as a rectifier so to control the dc voltage at output. The control challenge concerned with the unbalanced voltages in capacitor including the currents of all phases. Their suggested algorithm was on the basis of composite dynamic system concept, which considered the composite characteristic of the NPC converter, that is, the discrete and continuous dynamics, assuring consistent comprehensive asymptotic stability of the operation. Zhou et al [45] suggested model predictive power control (MPPC) to consider the commutating non-linearity constraints of the power converter system. This happened to be hopeful controlling method for 3φ phase 4 switches rectifiers (TPFSRs) since control of voltage balancing in capacitor and instant power were concurrently developed in this power converter type. But, being just one commutating vector was permitted in every control period, traditional MPPC (C-MPPC) might cause substantial ripples at output power that might badly downgrade the quality of the power in system. This was specifically valid for TPFSRs because of the restricted amount of commutating states including the limitation enforced by the control of voltage balancing in capacitor. They proposed a multiple vector MPPC method, which might decrease the ripples on active and reactive powers and attain voltage balance in capacitor using a fixed commutating frequency while enhancing TPFSR performance. They obtained an identical zero voltage vector and a capacitor voltage balancing systems to realize the suggested control method. Lastly, they compared outcomes to establish the suggested control technique is superior over the C-MPPC. Trinh et al [46] introduced a compensation approach to handle the measurement errors of both current and voltage in the 3φ PWM rectifier. The dc compensation and resizing measurement errors in both current and voltage introduced unwanted dc and imbalanced currents into 3φ input and consequently affected dc output voltages with ripples. So, they suggested a compensation method for measurement errors of current in which the dc compensation and resizing errors to estimate from the characteristics of the ripples of dc voltage at output using basic low pass and band pass filters. A sophisticated current controller was developed simultaneously using PI and two resonance controllers that resonated at the fundamental frequency ω_s of the grid. 2ω_s in the synchronous d-q reference frame was presented to dismiss the influence of dc compensation and resizing errors during measurement of voltages. The suggested compensation scheme was designed with no support from additional sensor and circuit, or accurate data about model specifications thus it could be believed to be economical and durable solution. Zhang et al [47] discussed decade long investigation methods of Deadbeat control (DBC) due to its easy design and adequate operation. Further, they discussed the scope of finite control set based model predictive control (FCS-MPC) for controlling power converters. FCS-MPC did not use a modulator and straightaway control commutating states with minimization of cost objective function unlike DBC. They proposed an enhanced FCS-MPCs method to increase steady state behavior by inducting vectors, two or three, within one control cycle. Further, they gave novel glimpses about composite vector based FCS-MPC for power converters through examination of its association with space vector modulation dependent DBC (SVM-DBC). Their research showed that both types of predictive techniques might be combined into a common structure while controlling aim was to decrease the error on tracking. The vector series and period of their suggested composite vector based FCS-MPC were straightaway rebuilt using SVM-DBC on comparison with count based vector option in traditional FCS-MPC. Jamma et al [48] proposed a direct power and torque control (DPTC) method to control 3φ PWM rectifier-applying a controller of adaptive neuro-fuzzy inference system (ANFIS) based to control coupled dc voltage regulation. Their research aim was to minimize the variation and to discard the effect of load induction motor drive (IMD) on coupled dc voltage. The application of PI controller could not meet these goals because of the issue of sensitivity over perturbations and constrained control range. An ANFIS based controller was developed to address these issues and output power at the inverter side is combined to the active power of reference at the rectifier side. The effectiveness of the suggested controlling method was contrasted to the PI controller to exhibit its performance.

4 CONCLUSION

This paper aimed to explore through surveying various technical literature relevant to control techniques of three phase rectifier primarily involved to reduce low order harmonics and improve power factor. The literature review further shows that the achievement of substantial enhancements in performance parameters namely mitigation of low order harmonics of voltage and current at input and output, improvement of power factor, commutating frequency, and relevant variables of various methods. It is believed that this review article will be greatly beneficial for the present research to explore the possibility of using novel techniques like neural networks, learning based controllers in mitigation of harmonic components and improvement of power factor of three phase rectifiers. Despite, superior developments were made in traditional approach such as harmonics distortion reduction and the power factor enhancement, they face drawbacks. In several instances, mathematical expressions are to be reduced to derive the solutions to address realistic extensive controlling methods. Still, it is found that present solutions are ineffective to process qualitative parameters.

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