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A Review on the AC Servomotor Control Systems

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Abstract: AC Servomotors are widely used in the industries for the control of static and dynamic loads. Precise control of position, speed, and torque are the main issues with the AC Servomotor. AC Servomotors are highly demanded by the industries to have a precise response under dynamic load conditions. Many control techniques are commercially available for the control of AC Servomotor under static and dynamic load conditions. However, all of these control techniques have advantages and limitations. Many investigations are done on the control of AC Servomotor, but comprehensive surveys on the control of AC Servomotor were still limited. In this paper, most of such commercially available control techniques are investigated, discussed, and compared. It was found that all of the available control techniques have drawbacks, such as step response issues, waveform oscillatory errors and fluctuations, instability of the system, switching losses, sensitivity to parameter variations and external disturbances, and low dynamic responses. There is no control technique available which could solve all the issues simultaneously.

Keywords: AC Servomotor, Control Stability, Dynamic Load, Static Load, Step Response, Control System

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1. INTRODUCTION

A servomotor is a motor employed for the control of position or speed in the closed-loop control systems. The functions of the servomotor are to turn over a wide range of speed and also to perform the control position and speed instructions given. DC and AC servomotors are utilized in applications due to their machine structure in general. When the condition is low power and variable speed, the AC servomotors are the ones favored in control systems due to its control capabilities [1–3]. Besides, the applications of the AC servomotors can be found in conveying technology, printing, wood processing, textile industry, plastics industry, food and packaging industry, packaging and filling plants, and machine tools. There are two types of AC servomotors available which are a squirrel cage asynchronous and a permanent magnet synchronous. In the field of control of mechanical linkages and robots, research works are mostly done only on the DC motors. A literature review regarding the AC servomotor motion control and tracking characteristics is limited since the AC servomotor technology is respectively new. AC servomotors applied in some research articles are overviewed herein. Moreover, Lin et al. [15] have conducted a study on simulation and dynamic performances of electrical machines; the transformer, the DC machine, the polyphase induction machine, the polyphase synchronous machine, and the single-phase induction machine with an electric machine simulation program. Takahashi [24] presented an environment to model and simulate mechatronic devices; electrical motors (AC and DC), electronics, fluid power and control, and mechanical systems. Also, Seki et al. [10] have described a study on a high-performance servo drive system and characteristics of a salient pole permanent magnet motor. Wang et al. [32] analyzed the performances of AC servo drives utilizing synchronous and asynchronous motors. A mathematical model is given with the control scheme and supported by experimental results. Besides, a study done by Sravya [11] completed a robust control of an AC induction servomotor for a motion-control system. Plus, X. Li [43] introduced a comparative study between two permanent magnet AC machines by using numerical simulation and also experimentally. The simulations were included for a two-joint rigid robot directly driven by induction motors. Furthermore, Zhang et al. [37] have worked on high dynamic speed sensorless AC drives. Experimental verification was achieved with an induction motor. The on-line-mode parameter tuning was applied to eliminate the steady-state error. Ollervides et al. [18] have dealt with the problem of mechanical resonance in a system comprising a permanent magnet synchronous servomotor and a load with experimental verification. A study on the performance of PD controlled servo systems was conducted by F. Lin et al. [15]. A mathematical model was presented with simulation results and the experimental implementation was included. In a motion control and implementation, X. Lx [13] performed motion control of robots by induction motors to trace the given directions by introducing a current controller. A complete PM AC servomotor model was developed by P. Puttaswamy et al. [21] too, which implemented a neural network self-tuning PI control scheme. The authors presented the experimental results in the study.

2. CONTROL METHODS

Many control methods are available for AC Servomotor. Some of the control systems focus on the position control only while some control systems focus on the speed or torque control, respectively. However, some control systems focus on the control of position, speed, and torque of the AC Servomotor at the same time.

2.1 POSITION CONTROL

In this part of the paper, the control techniques for the position control of the AC Servomotor are discussed. These control methods are only used for the position control of the motor.

M. Sazawa and K. Ohishi designed a control system based on a fast continuous path tracking mechanism for the flexible position control in 2009 [2]. In this control strategy, the saturation of the torque and the coordinated-motion were taken into account. For the starting and final position, large accelerated or decelerated torques were needed; thus, the PI controller had small loops of the control acceleration to provide some output. This limited output method, compensated for the corresponding output and constructed the limiter of the speed controller. On the other hand, a time of deceleration, which was the duration from the commencing brake time to the finishing brake time, was proposed, and within this time, the control system was decelerated utilizing the highest torque. The commencing time of the brake was known by the torque of the load and the targeted position. The distance of the movement was delighted as the error of the position until the targeted position. This control technique had a good step response, and it did not have oscillatory errors and overshoot. Moreover, it also reduced the tracking error that occurred because of the dynamic load. However, it did not fully eliminate the error. Its tracking radius error was 0.02 rad. The system complexity and high gains of the controller may have consumed a lot of energy due to the PI controller. The system settled at 1.041 seconds, whereas under conventional fast continuous path tracking control, the system settled at 1.046 seconds.

M. Vijayakarthick et al. proposed a new Modified Repetitive Control Strategy to track a position control performance of AC Servomotor in 2012 [3]. The proposed control method was used to track the reference signal and reject the load signal and was designed based on the Principle of Internal Model. IMP states that perfect tracking can be achieved, and a signal can be completely rejected if the closed-loop model is stable. For the high-frequency signal, the stability of the system could be affected by the noise. This problem could be solved by adding a low pass filter to the control loop. The sensitivity function could be taken into consideration because the stability had a direct relation with the sensitivity; in addition, a rational factor was incorporated. Moreover, this control method was not affected by external disturbances or load variations. This repetitive controller did not affect the stability of the system. It had a good adaptive tracking ability, and in a practical situation, it was very robust opposing the noises. Its theories of control and knowledge of the system were not required to be very difficult or complicated. Furthermore, according to the experimental results, there was an existence of the tracking error in the output waveform, but this error was less than PD and conventional repetitive control strategy. The error started reducing after 70 seconds, subsequently existed some delay in the tracking response of the periodic reference trajectories. The settling time of the system was around 100 seconds under a 2% tolerance level.

In order to meet out the problem with Iterative Learning Control (ILC), an Enhanced Iterative Learning Control (EILC) method was proposed by S. Sathishbabu and P. K. Bhaba in 2012 [4]. The ILC control scheme features were learning filter and low-pass filter; the rate at which the error signal was converged could be known from the learning gains. This version was improved by EILC, where the main idea in this version was that the error signal was applied by the Filter before the control signal for the next trial was computed. Practically, the developed processes may have caused some unexpected variations from the main or actual process. Subsequently, few disturbances caused by the Filter could occur and affect the closed-loop stability in the presence of high frequencies. However, this issue could be reduced by adding a Low Pass Filter in the loop of the control. Furthermore, this control method also provided good robustness opposing to the noises in the practical. It did not need a complicated environmental model, theories of control, and information of the system. Even though the absolute error in the tracking error response of this system was less than ILC, some errors still existed and should have been further reduced. Its tracking error response for the first five iterations was huge. The absolute error at the second iteration was 1200 radians. After the second iteration, the error started to reduce, and finally, after eight iterations, it reached up to 80 radians and stayed at the same value for the rest of the iterations. This control system also was affected by the load variation.

Although the reference waveforms were periodic in the practical, the conventional controllers were not able to track it properly with a good performance. To reduce this problem, A.Ali and A. Alquhali suggested an AIMC strategy [5]. This strategy states that the control scheme can be developed perfectly if the controller is designed based on the definite scheme of process Gp(s). This indicated that the identifier needed to have complete knowledge about the process. The feedback was only needed if the knowledge about the process was incomplete or inaccurate. By using mathematical equations, the transfer function Gp(s) of the AC servo system was identified. Plus, Bode plot techniques were utilized to analyze the closed-loop transfer function of the motor. In general, it was assured that IMC achievements were better than the PID controller, specifically, in terms of rising time, settling time, overshoot, and its greater gain margin. Even though IMC was better than PID in terms of performance, it still required further improvement to have the ability to control the dynamic load and remove the transient and steady-state errors fully. The settling time of the AIMC controller was 8.13 seconds under a 2% tolerance level.

A research paper conducted by N. Wang and W. Lin in 2016 initiated a robust tracking control method [6]. This method guaranteed the design of the controller so that the AC Servomotor could have accurate tracking of the position. The proposed strategy was implemented on the base of vector control together besides the law of mechanics of the Screw Ball and the development of a recent dynamic model. The formulation of precise position tracking control was done. Using Lyapunov access, a convex optimization approach was used to formulate the existence conditions for the controller. To control the motion of the Motor, some more conditions needed to be considered, such as non-linear effects of the friction and unknown disturbances in the system. The authors also stated that the Neural Network could also be used to make the position control more accurate and to approximate the non-linear friction effects. The adaptive control method could be used to compensate for the parameter variations. Besides, this proposed control strategy had a good dynamic response but could lead to transient errors in the step response. The system position control waveform settling time was 12 seconds under a 2% tolerance level in uncertainty cases. Also, there were some position tracking errors as the output signal never tracked the input signal exactly at any point. Hence, the system fault tolerance control and network framework needed further improvement.

2.2 SPEED CONTROL

In this part of the paper, the available control techniques for speed control of the AC Servomotor are discussed. These control methods are only used for the speed control of the motor.

A study conducted by F. F. Cheng and S. N. Yeh in 1993 suggested a novel fuzzy logic controller (FLC) utilized to control the speed of the AC Servomotor [7]. The authors used a microprocessor to reduce the circuit components for price reduction and the enhancement of reliability. In order to control the motor torque instantaneously, field orientation was indirectly endorsed, including the current-regulated PWM and VSI. The functions of membership of FLC were known by the normalization of the input variables and the predefinition of the linguistic codes. For the high and fast performance AC servo system, a rules table was proposed based on the following two concepts. Firstly, if the change in the error of the angular velocity was zero, and the output was set to a value, the controller would maintain the output. Secondly, change in the output was conducted based on the magnitude and the error in the angular velocity and the change of error in the angular velocity signs, which means whenever there was a departure among both of the values that were existing, the output recovered to set. The implementation of 49 rules was done by utilizing the linguistic codes; the output variables were also composed of linguistic codes. When there was equality between the input and the output variables, the relation led to unity. The relation was 0.5 degrees if near to each other and zero degrees, for others. Furthermore, this control method is a low cost, simplified hardware, and reliable. It has a good dynamic response, and the switching loss was small, minimized the chattering phenomenon, and the harmonics in the current. However, it also had some drawbacks, such as viscous friction existed in practical. The control system contained reduced torque pulsations, step response issues, complex calculations, and heavy parameter variations.

Besides, E. Yolacan and M. Aydin conducted an experiment on the vector-based speed control of permanent magnet AC servomotor with FEA in 2012 [8]. According to the authors, in the Vector Control (Field Oriented Control) of the AC machine, three-phase AC stator current was transformed into a d-q axis rotating reference frame. This method used the current and speed variables of the motor, which were compared with the reference signal. The PI regulators were used for reducing the error to zero that was generated from the differences between the measured and the reference signal. The vector control technique was implemented based on the phase and current magnitude. Plus, the three-phase currents of the motor were measured and sent to the controller. The controller would calculate the convenient signals to generate the Pulse Width Modulation (PWM) signals with respect to the phase current and the position of the rotor. In this experiment, the Ds1104 dSpace control board was used. Based on the results obtained from the experiment, this control method has advantages such as a good step response, no overshoot, a rise time of 1.5 seconds, and a settling time of 2.85 seconds. Also, the dynamic torque response in this control system was very low, and it was sensitive to parameter variations in the control system.

In addition, I. Kadan et al. designed a low-speed control of AC servomotors in no-load condition [9]. The designed control method utilized adjustable torque ramp option. During the mode of torque control, the torque ramp option was specified to know the supplied control voltage of the drive proportional to the specific amount of torque. A proper control signal could be sent to the drive-by assigning a proper value to the torque ramp option. Since the control signal was properly measured, and the prior amplitudes of the noises were known. Hence, this helped to reduce the effects of the noise in the later iterations. Moreover, the motor torque was regulated by scaling down the least noise affected signal by the drive. As the drives were strongly safeguarded, the noise could not affect the internal signal of the drive. Dynamic modeling was done for the rotating shaft of the motor. Also, the motor speed could be well regulated at desired values, and the effect of noise could be reduced to some extent through sending a properly measured signal to the drive. The control voltages had some fluctuations because of a key attached to the shaft. The key weight became noticeable because there was no load attached to the motor shaft, and the motor speed was very low. Even though the torque ramp parameter reduced the noise in the system to some point, the motor speed still contained some fluctuations and oscillations.

Another research paper was published by Y. Seki et al., in 2015, suggesting another control strategy [10]. The suggested control strategy improved the voltage utilization on the constraint of the region of flux weakening by the combination method of flux weakening control and the Inverter modulation arrangement. When saturation in the voltage appeared, the control of flux-weakening operated utilizing the d-axis current and terminated the saturation in the voltage. Saturation in the voltage occurred when the voltage vector crossed the output limitation. In order to keep this vector in the inscribed circle, the desired d-axis referenced current was known by the inverter control scheme. Furthermore, the speed control arrangement of the Servo system was considered by the phenomenon of the windup and the control methodology of the conventional flux weakening. The speed response tracked the reference speed and determined the reference q-axis current. If the reference q-axis current was restricted by the current limiter, the feedback saturated q-axis current could correct the PI controller. Since the Inverter output voltage had a limit, therefore when the reference voltage crossed this limit, the inverter would not be able to produce the referenced output. To avoid instability, saturation in the voltage was considered to correct the integral calculation of the current controller. The d-axis current controller was not employed by the anti-windup strategy of the control. This was because the de-coupling control was disturbed by the feedback of the voltage saturation. In short, this control method brought the improvement in the Inverter voltage utilization, the reduction of copper loss, and good transient response. The copper loss was reduced compared to the conventional differential signal control method, but it still contained at the quantity of 12% under 25% load condition and 14% under 75% load condition. The d-axis current used for the control of the flux weakening was reduced from 0.99A to 0.71A. On the other hand, the expending voltage restrictions caused the voltage saturation to occur. The speed and current responses contained oscillatory errors which may affect the accuracy of the control system.

Speed control of electric drives using Active Disturbance Rejection Control was initiated by Sravya K et al. in 2016 [11]. In this control method, first of all, the Servomotor was modeled using mathematical equations. Phase voltages, flux linkages, currents, electromagnetic torque, rotor angle, and speed were obtained from the dq0 equivalent circuit of the motor. In this control strategy, three ADRC loops were designed; two were used for current control, and another one was used for the purpose of speed control. Furthermore, firstly, the input reference signal, was tracked by the tracking differentiator. Afterward, the Tracking Differentiator (TD) organized the process of the transition and produced the derivative value of the signal that was supplied at the input. The deviations of the input could be smoothened in order to reduce the overshoot at the output. The Extended State Observer (ESO) was utilized to evaluate the system disruption and uncertain model's effects. Also, Non-Linear State Error Feedback (NLSEF) was used to produce the control rules for the system by combining the output of ESO and TD, where ESO being a fast tracker, compensated some disturbances. For that reason, NLSEF and TD were replaced with proportional parameters to meet the desired responses. In short, ADRC control could compress the unknown disturbances internally or externally more accurately than PI regulators. ADRC was better than conventional PI regulators with respect to rising time and settling time. Overall, the improvement in the speed response and dynamic speed response of ADRC based control of AC Servomotor were still needed.

Moreover, a study on the design of the Fuzzy Logic Controller (FLC) for speed regulation of Permanent Magnet Synchronous Motor dually driven system considering the complexity of fuzzy designs was carried out by B. Shikkewal and V. Nandanwar in 2012 [12]. The alternate methodology in designing of the fuzzy system was to tune by the Universe of Discourse method. This involved modifying the rules and also the number of rules in which a scaling factor was employed before each input and after each output of the control structure. In many cases, this scaling factor was taken by trials and error methods. For the study purposes, two structures, namely standard design, and the case design were considered. The standard structure was designed with 49 rules consisting of seven membership functions for each variable (error and rate of change of error) designed by a conventional procedure. Meanwhile, in the case design, the structure consisted of Nine rules with Three membership functions designed by tuning with the Universe of Discourse method. Plus, the Mamdani Fuzzy Inference type was used for a Fuzzy Inference System scheme. Both scenarios were compared and tested for different loads and wider ranges of speed. It was inferred from the analysis that both scenarios resulted in a similar performance, and thus, a number of rules could minimize the FLC system's complexity. Besides, the major advantage of fuzzy logic control was the capability to handle impreciseness, its high adaptability, and free from mathematical modeling (because of its flexibility to operate with linguistic schemes). However, the setback with the design of the FLC scheme was that it required some intuitive understanding of the process. The simulation analysis also expressed that tuning by alternate approach resulted in faster rise time. The scaling factor played a prominent role in stability and oscillations. Thus, the scaling factor had to be addressed with proper care to avoid some fluctuations in the speed response.

Apart from improving the dynamic performance, in order to simplify the tuning methodology, the conventional ARDC scheme was decoupled, such that disturbance rejection was independent of the reference tracking. This control method is suggested by X. R. X. Lx et al. in their research paper in 2015 [13]. According to the authors, the analysis was carried out on the PMSM drive for better regulation of speed. In the conventional ADRC control structure, the proportional coefficient parameter contained the coupled effect on tracking and disturbance rejection. The underlying phenomenon behind the proposed scheme was the estimation of total disturbance rather than the estimation of target disturbance alone. Plus, the velocity feedback contained noise, which was generally eliminated by using Low Pass Filter. However, the introduction of filter affected the system closed-loop performances due to the lag associated with it. Hence, a velocity estimator was used to improve performance. The existing framework of ESO was analyzed for different structural possibilities, and the modified Linear Extended State Observer was proposed. With the LESO scheme, tuning became easier by making the disturbance attenuation effect separated from the proportional coefficient parameter. This resulted in the decoupled ADRC scheme. The proposed scheme was analyzed, and the validation was carried out using a real-time implementation of the control algorithm using d-SPACE DS1103. The proposed scheme was analyzed for different tracking and disturbance rejection performance. According to the results obtained, it was inferred that in the case of conventional ADRC, changes in the proportional coefficient parameter affected the disturbance rejection property to a great extent. In this case, a perfect trade-off was maintained for optimal tracking and disturbance rejection, whereas in the decoupled ADRC scheme, the LESO bandwidth and proportional coefficient were independent of each other, and the system could have better performance with easy tuning. However, it was also inferred that bandwidth of

ESO affected the tracking performance with the introduction of ripples in the case of conventional ADRC, and was not affected in the case of decoupled ADRC. In the case of the decoupled ADRC, the speed and current response of the system contained a lot of oscillations.

2.3 POSITION, SPEED AND TORQUE CONTROL

In this part of the paper, the control techniques used to control the position, speed, and torque of the motor simultaneously are discussed.

A control method used to control the position, speed, and torque of the motor simultaneously was proposed by Z. Chen et al., in 2001 [14]. In this method, multi-layer momentum neural networks of back-propagation joined with the PID controller were used to control the Servomotor. The multi-layer neural network contained Three layers, which were the input, hidden, and output layers. Each signal flows over a weight known as synaptic weight. The polarities of weights depended on the acceleration of the signals. All the input signals were accumulated and transferred to the output signal through the summing node using a transfer function. The transfer function could be either step type or threshold type. It would transfer one if the input outpaces the threshold value or else zero. The desired pattern could be achieved by training this network. Plus, since the scattered intelligence devoted by the weights, therefore this network was able to learn. Moreover, this control strategy had a fast dynamic performance and there was no overshoot. However, using this control system, the rise time of the speed response would be two seconds, which would lead the system to be slow.

F. J. Lin et al. developed the Three-position controllers, which were Variable Structure Controller (VSC), Variable Structure Adaptive (VSA) controller, and Variable Structure Direct Adaptive controller (VSDA) [15]. These three controllers worked on the same principle. The VSC and VSA were improved and replaced by VSDA. This control system contained Two main parts, which were the VSDA controller and the Servomotor drive system. The conventional drive system was supported by the VSDA controller, which provided great advantages. VSDA contained the PD controller, variable structure law, and direct adaptive law. In the design of the VSDA controller, for the practical operation, it was hard to achieve the uncertainty constraints in advance. At the same time, a conservative design control scheme caused the chattering issue more severe. For that reason, the Direct Adaptive law was used in this controller, designed to estimate the uncertainty bounds. If there were no load disturbances and parameter variations in the system, a very small positive value of variable structure law would be enough to keep the amplitude of chattering small and hold the system stable. However, if external load disturbances and parameter variations were present, departing from the sliding surface, it would need the regular update of variable structure law, which was created by the adaptive structure to drive the trajectories of the system back towards the sliding surface quickly. One of the advantages of this control system is that it had good robustness to parameter variations and external disturbances. Also, it did not require knowledge of uncertainty bounds. This control method also had good performance with reduced chattering, but the chattering still existed and should have been even reduced more. The load regulation response of this control system was not fully improved as it was a little bit sluggish.

Moreover, an Iterative Learning control method was supported by the fact that the same recreating effects would lead to the same error at each time or each run, the control signal could be adapted by the recording of such errors. In the next run, this control signal was assigned to the process for the reason to reduce the error. So, the error decreased with the increasing number of trials. This control method introduced a new method to remove the zero-crossing and the effect of the dead-time from the PWM Inverter's output waveform. For the creation of an appropriate dead-time compensation voltage, a learning algorithm and PI regulators were plugged in parallel for the creation of dead-time compensation voltage. With the help of the motor current and the angle of the rotor, the actual currents were forced by the learning algorithm for the tracking of the reference current. With a start in learning, the error between the actual current and reference current decreased with time. With further progress in the process, d-q current approached to reference current without the requirement of a proper dead time compensating signal generation. Moreover, after achieving an acceptable convergence, the learning process was ended, and the learned compensating signals were recorded. By making the learning process offline for different values of the load current and the operating frequency, the learning process became faster. These signals were stored in memory. At the time of the online operation, the operating frequency of the drive and the currents of the load were identified with the proper selection of these stored patterns. These were superposed to the output of the PI regulator. To take the external disturbances into account, Periodic online learning might be carried [16]. In short, as the proposed learning control and PI control operated together, for that reason, the oscillations and fluctuations in the current waveform were removed. However, removing these oscillating errors took a few cycles that may have affected the current response.

Another study conducted by S. Zorlu et al. in 2006 also suggested a new control technique using a custom-designed Motion Control Card [17]. In this technique, the implementation of control is done utilizing a Personal Computer (PC) with a Motion Control Card. The torque could also be controlled using the Motion Control Card (MCC). In this application, a Low Pass Filter was used to filter the Encoder signals. A PM DC generator was connected at the output shaft of the Servomotor, and then a dynamic load was connected at the output of the generator to observe the nature of the Servomotor under the different load conditions. Field-effect Sensors were used in the power circuit of the Servomotor to measure the separate voltages and current. Also, DC bus voltage and motor currents were measured using voltage and the current Sensors. The Inverter was driven by four 15V isolated voltage sources, and the MCC was connected to the PC using Industry Standard Architecture (ISA) bus. Eight-bit port at the output of the Inverter signals, Analog to Digital Converter (ADC), and Encoder chips were utilized to measure the voltage and current. ADC was used in order to have Zero phase shifts between the signals. The speed was measured using the HTCL 2016 chip, and an algorithm was built to realize the rotor's initial position. Based on the results obtained, the current and voltage waveforms contained oscillations, which may have led the system to be noisy. This control method had a fast-dynamic response where its settling time was very less, but an average error still existed in the speed response of the system. The Motor at half load could not achieve the targeted speed as fast as it could achieve at full load.

Furthermore, an electronic feedback control system based on the embedded Digital Signal Controller (DSC) Microcontroller is also another control approach designed by J. Ollervides et al. in 2011 [18]. The control method consisted of a Switch power amplifier which fed Actuator inputs that attributed a dual full H-bridge driver. The driver IC was embedded with the DSC Microcontroller. Two quantities of Hall effect current Sensors were used to obtain the feedback current. Besides, the angular velocity and position of the shaft of the motor were measured by an incremental optical encoder. The Hybrid Stepper Servomotor was used as an Actuator. The two-phase hybrid Stepper Servomotor contained two electrical components and one mechanical component. These components were connected by the back-EMF (Electromotive Force) and the transmission of torque. This control method was aimed for position tracking and torque control. Torque could be controlled if the difference between actual current and the desired current was zero. In order to keep this difference as Zero or to make the stator current trajectories follow the desired current trajectories, the input control voltage was designed. The switch power amplifier was used to reproduce the signal that was fed to the Motor, and it also worked as an integrated circuit for current sensing. Lastly, this electronic control system of the Servomotor provided enormous benefits in portable drive system applications. On the other side, because of the electronic drive network, the cost and complexity of the control system increased and also consist of many angular errors and oscillatory errors in the shaft rotor position of the motor.

Besides, L. Zhang et al. proposed another control system based on the XC164CM microcontroller in 2012 [19]. In this control system, the Incremental Encoder was used to achieve the angular position of the AC Servomotor, since the speed was determined from the position that changed over time. This value and the feedback value were both sent to a speed-PID controller for the adjustment. This speed-PID controller was used to adjust the output (d, q-axis current), and then this output value was sent to the current-PID adjuster. Three-phase stator current was detected by ACS712 (the hall device). Plus, the Clark and Park transformations were utilized to convert the three-phase current to d-axis and q-axis currents. This current was transferred to the current-PID controller, and the resulted signal was transferred to the Inverter. A Space Vector Pulse Width Modulation (SVPWM) signal was generated from the CCU6 unit, whose input was the two-phase current, which was the conversion of the Inverter output using Park inverse transformation. This SVPWM signal was then sent back to the Inverter in order to generate a PWM signal to control the Motor. The benefit of this control system is that this control system had simplified hardware design and good reliability. On the contrary side, the Inverter output contained a lot of oscillatory errors, which may have led the system to be noisy. Also, since the PID controller was used, because of its high gains, it may have consumed more energy and led the system to be noisy in practical as proved by the results in Chapter Four.

Apart from that, a PLC controller used to control the three-phase AC servomotor drive was initiated by M. Sreejeth et al. in 2012 [20]. The authors explained that a PWM signal from an AC drive was sent to the stator windings of the motor. The Motor was controlled by the PLC output, established on the mentioned ladder logic. Thus, the Motor parameters were able to change online and offline. However, there were some specific tasks that needed to be done in the online mode and offline mode. In online mode, the Motor parameters such as average load, speed, and feedback pulses, etc. were recorded. In offline mode, the Motor drive could be directly fed by the parameters. Also, for offline control mode, the parameters could be directly fed to the Servomotor drive. A data bus named Modbus-RTU required field data from the Motor and transmitted it to the PC for the process. The data bus was also used to scatter the logical signals towards the Servo drive obtained from the PLC. Besides, there was an error between the reference speed and original speed from which the reference torque was generated utilizing the speed controller. During the constant torque operation, the ratio of the reference torque and the torque constant of the Motor was treated in order to calculate the reference quadrature axis current. The phase currents of the stator were achieved by employing the park's inverse transform with the help of the rotor position feedback and d-q axis currents. The output was fed to the hysteresis-band-controller after comparing the reference current with the actual current using the PWM converter. The hysteresis-band-controller output was used as a gate pulse for the Inverter, and the variable frequency and voltage of the Inverter were supplied to the stator windings of the motor in order to achieve the commanded speed. Plus, with high speed and high current, the Total Harmonic Distortion (THD) level was lower, and Motor was in a good performance. However, the harmonics in the line current increased when the Motor was running at a lower speed. Hence there were effects on the precision and performance of the drive. At 25% load and 1500rpm speed, the harmonics in the line current were 71.7%, and at 3000rpm, this distortion reduced to 61.7%. The speed response of the system was affected by fluctuations.

The servo motor also could be controlled by utilizing a Multi-layer Neural Network, as discussed in the research paper written by P. S. Puttaswamy and K. D. Dhruve in 2013 [21]. This method adopted the use of a neural network for the adaptive direct torque control of AC Servomotor. The Artificial Neural Network had higher precise control than a conventional PID controller. This is due to the fact that the proposed method could tune the conventional PID controller parameters more accurately with the neural network technology. To demonstrate the speed control loops, a PWM inverter fed the motor. The speed control loop that had a PID controller produced the quadrature axis current. This quadrature current produced the electromagnetic motor torque. This method was known as DTC. The d-q frame was transformed into the a-b frame, and the resulting currents were fed to the motor. The advantage of this control method is it has a good speed control performance for larger and smaller variations in Motor parameters and the load conditions. Also, the motor achieved the required speed after a small overshoot and some delay. The performance of the system was further improved for small parameter variations rather than large parameter variations.

In addition, J. Yin et al. proposed another servo motor controller, which utilizes a Fuzzy Adaptive PID based on the DSP [22]. This control strategy was adopted using Three control loops, which were the current loop, speed loop, and position loop. This control strategy played a role in improving the dynamic response of the system and adjusting the faults at the slow speed. This control strategy was designed based on the linear motor position motion law, according to which a large error could be quickly eliminated by increasing the weight of the error control function. To eliminate the overshoot of the system with an increase in error, the weight of the error-change control action was increased. Also, the addition of a special Analog to Digital (A/D) acquisition Chip helped to improve the precision of the system, which could recognize the feedback currents and the collection conversion. The system used a Chebyshev type II filter for digital filtering. In short, this control system had a wide speed range and did not need the modeling of the object that was going to be controlled. The positioning accuracy was high, but the position control curve contained small overshoot errors, and the rise time was two seconds. Plus, the settling time was 2.5 seconds, and the proposed control procedure led to the frequency of the system to fluctuate.

Another control approach was proposed by K. Matsuura et al. in 2014 [23]. According to the authors, in the AC Servomotor, the phase currents were detected by the Current Sensors. Three Current Sensors were used to measure the three-phase current. Sometimes two Current Sensors were also used (such as u-phase and w- phase). However, the problem with this method was that these sensors had characteristics variations such as gain and offset variations. The current ripples were caused due to this issue. To overcome this problem, a DC-link Current Sensor was practiced. After the measurement of this current, the construction of a three-phase current was done utilizing a three-phase algorithm. For the three-phase current to be not affected, the current sensor should have had an offset, but if there was gain variation, the current would be affected. Hence, it was a necessity to recognize and compensate for the variations in the gain of the sensors. Moreover, a reconstruction circuit was obtained by using multiple RC series circuits. Six samples and hold circuits were needed to achieve the dynamics of the DC-link current for each Switch. Also, the Inverter was driven using the SVPWM technique, so that the convenience of achieving the dynamics in the DC-link current prior and after the switching was increased. Lastly, by using this method, there was no occurrence of the current ripples. This is because only a single sensor was utilized for the detection of the current, and secondly, the current measurement gain deviation was compensated. However, there was a presence of electrical parameter variations in the practical work, and some current variations in reconstructed current still existed, which could affect the dynamic behavior of the system.

T. Takahashi and I. Rectifier designed a controller using a single chip motion control engine IC [24]. The authors used the IRMCK201 IC, which was a single Chip entire solution for the closed-loop torque and speed control of the AC drives. This engine did not require complex AC servo algorithm development, and with the use of this IC, a complete control strategy could be implemented with a minimum number of components and design effort. Furthermore, this IC did not only contain motion peripheral functions (such as PWM, current sensing interface and Encoder counter circuit, etc.), but it also contained complete algorithms for speed and field orientation in the hardware form, named as Motion Control Engine (MCE). Also, this control engine contained control elements such as Proportional Integral, Clark transformation, vector rotator, etc. This IC did not require any coding or programming. Hence it could be easily tuned and also could adapt to new motor parameters easily. Besides, it contained memory registers that could be scanned or written using a mating Microprocessor RS232C by serially interfacing it with a computer. The scanning and writing of the registers could be done using a computer. For instance, if a specific value for the switching frequency was chosen, then it could be simply written to the specific register. The benefits of this type of controller are that the IC computed very fast for the closed-loop control algorithm, which led to a good dynamic performance of the speed and torque of the system. It was a single-chip solution for complete closed-loop control. Plus, it could be easily tuned with different specifications holding Motors, which helped to implement a control algorithm easily. The torque control loop had a good step response, yet it contained small oscillations. Lastly, its voltage switching waveform and motor current waveforms contained oscillations and were not smooth, which may cause noise in the practical.

In harsh environments such as underwater, the sensor of the Motor was one of the main issues. Therefore, the Sensor-less Servo system was suggested and implemented by B. Allotta et al. [25]. One of the critical parts of the Sensor-less control algorithm was the position-speed estimation. The Filter that had to be implemented to estimate the rotor position in order to perform an optimal commutation of the currents on windings. The most common technique for the Sensor-less control strategy of PMSM was established on the observation of back-EMF as emf was proportional to the rotor speed. This technique performed well when the Motor spine at a speed over 10-20% of the nominal value. As a result, the feed-forward start-up of the Motor was required. Another technique was based on the injecting signal that excited the machines at frequencies that were different from the operating frequency of the machine and with a negligible influence on the mechanical behavior of the machine. However, this kind of method required accurate current measurement and precise and reliable current Sensors. For PMSM with star-connected windings, it was also possible to perform Direct Flux Control that was able to directly estimate the motor flux linkages. Plus, an Improvement was done in the smart back-EMF estimators that were the determination of the rotor speed and position through back-EMF estimation.

The first part of the estimator generated the esteem of the back-EMF and the second part estimated the rotor speed and position through back-EMF. In short, the robustness of the controller against a harsh environment is that the real speed of the motor was lower than the reference speed. This led to an average error between the estimated speed and reference speed of the motor. Also, the current and voltage waveforms contained a lot of oscillations.

Furthermore, C. H. Yan and J. H. Hui designed a full-closed loop servo control system in 2015 [26]. The semi-closed loop control system was widely used but for the enhanced control precision, the full-closed loop method was introduced. Gear Measuring Center used the technology of the measurement for Four axes which were X (tangential movement), Y (radial movement), Z (axial movement) and C (spindle rotary movement) axes. These axes were directed by the Servomotor using the numerical control method in order to understand the linkages between these axes. Besides, two ways communication was constructed between a single board computer and a motion controller. The computer sent motion command to the controller based on the received motion state from the controller. The position of individual axes in real-time was measured using circular grating. In the semi-closed loop control method, the encoder was utilized as a speed closed-loop control as well as position closed-loop control but some errors existed in the transmission chain. To overcome this defect, a grating was used as position closed-loop control, so the Encoder would only work as speed closed-loop control. The speed closed-loop contained Three internal closed-loops feedback control systems (loop of the current, loop of the speed and loop of the position). The current-loop was created internally in the drive and it was used to improve the dynamic response of the system. As a conclusion, this control system had no distinct sensitivity to its components fluctuations. The control method could improve the overall performance of the Motor. Yet, the drawbacks of this control method were it was more expensive and complex, there consisted risk of instability, and it may have created an oscillatory response and reduced the overall gain of the system.

Besides, an automatic control loop tuning initiated by S.-M. Yang and K.-W. Lin's study in 2015 presented a new scheme for the AC Servomotor drives parameters; the determination and auto-tuning [27]. For the current control loop, the determination of the electrical parameters such as inductance and resistance was done. On the other side, for the speed and position loop tuning, the determination of mechanical parameters and torque constant were done. According to the authors, the drive contained two inner loops for the current control and two outer loops for the speed and position control. The path in the speed loop was realized with the speed command. The PI regulators were utilized in the q and d axes current controllers and there was a limitation of at least half of the rated single-phase voltage. Also, the decoupling of the cross-coupling and back-emf voltages were done utilizing the predicted speed of the rotor and the electrical parameters of the system. The cross-coupling voltages and back-emf voltages were decoupled using the estimated electrical parameters and rotor speed. To prevent the error caused by the motion of the rotor, the resistance of the stator should have been known. The measurement of this resistance was done by employing a pulse of d-axis voltage. Based on this pulse, the measurement of the d-axis current at the steady-state was performed and then from this measurement, the resistance was calculated. The inductance was calculated by the measurement of the peak current, which was done by applying pulses of q and d axes voltages. Mechanical Parameters, Feed-forward voltage and torque constant were known by utilizing the theoretical current and speed waveforms. In practice, the entire auto-tuning procedure took roughly 1.4 seconds for accomplishment. The advantages of this control system are this method led to a good dynamic response, although the parameter identification was not free of errors. Next, the transient response and the frequency of the closed-loop showed consistency with the tuning. However, some errors existed in the measurement of auto-identified parameters when compared with manual measurement, these errors were within 10% and at the same time. The system current waveforms contained many oscillatory errors and these errors should have been reduced for further control precision.

Next, Y. Sang et al. proposed a practical AC servo motor controller based on the STM32 microcontroller in their research paper in 2015 [28]. The proposed servo drive had three control modes, which were the position, speed, and torque. For speed control, the Microcontroller produced two-way pulse signals and then the signal was fed to the servo drive to control the Motor. The Encoder produced the feedback signal. The rotation angle of the Servomotor was controlled by the deviation signals that were generated by the comparison of the target value and feedback value. The position control accuracy was depending on the number of pulses that encoder produced per revolution. This particular Servomotor had two input ways of speed command, analog input and register input. Moreover, the Microcontroller realized the speed control of Motor through digital-to-analog conversion. For instance, a higher value of analog voltage led to a higher value of speed. Finally, closed-loop control was known by the feedback of speed loop Encoder. On the other hand, the torque was controlled by the produced instruction of the Chip through the digital-to-analog conversion to be sent to the CN1 terminal of the drive. In such a way, the Servo drive would rely on the internal current loop to realize closed-loop control. The current loop was used to determine the anti-interference ability and response speed of the system. Lastly, the position loop was the most important part of the stability of the system. The actual position from the feedback loop was compared with the target position set and then position regulator produced speed commands. In short, this control system had a precise static performance. It had a simple hardware circuit, strong real-time performance, low cost, fast processing speed, and reliable operation. However, this control system had two drawbacks, firstly, while adjusting the gain in manual mode, machine rigidity and surroundings had an enormous influence on the selection of Bandwidth. Secondly, the transmission inertia affected the stability and dynamic response of the Servomotor.

In the conventional AC drives the performance of the current loop was affected by the saturation of the magnetism. This affected performance subjected to the precision of tracking and the optimized methods like field weakening. An algorithm was used to control the current vector trajectory for the production of perfect current that produced torque within the limit of the supplied voltage. This algorithm is designed by J. Bermingham et al. and the principle was named field weakening [29]. According to the authors, the optimized torque current was calculated by utilizing the compensated PI regulator based on the voltage vector control method. The levels of the optimized torque under dynamic speed and system parameters were achieved through voltage vector trajectory commands generated by this algorithm. In this scheme, the voltage commands were generated under Four operation conditions, which laid within the speed and current boundaries of the motor. The voltage vector commands were implemented utilizing the voltage control strategy. Also, these commands were used to prevent the interaction or the sensitivity among the current loop and voltage loop. The voltage loops played a vital role in the regulation of the Motor voltage at the defined boundaries. This occurred when the realization of the current commands of the drive could not be done in the field weakening region. The decoupling process ensures that the d and q axes voltage control loops controlled the d and q axes current control loops respectively. In conclusion, this control system was robust against the effects of large parameter variations and its speed range and torque per set point of the speed were high. Plus, the voltage-vector control maintained continues Motor voltage and eliminated the risk of the degradation in the performance in the field weakening region. The principle of field weakening was comprehensive in terms of the theories but practically, it was difficult to achieve the objective correctly. Its voltage and current waveforms were not very smooth which may affect the speed and torque performances of the Motor.'

Apart from that, the performance improvement of the torque ripple suppression by using the FLC approach for PMSM was proposed by M. Gong et al. in 2015 [30]. In this proposed design, the conventional Direct Torque Control (DTC) scheme was replaced with the FLC structures. The hysteresis controller of the DTC scheme considered only the signs of flux and torque error rather than their amplitudes. If the amplitude of the errors exceeded the hysteresis boundary, then only vectors were changed else they remained the same irrespective of how large or small the error was. Besides, these vectors of voltages given by Voltage Source Inverter (VSI) with flux and torque error information were used to control the Motor. The authors also employed discrete control methodology, which was performed with respect to the defined discrete instances. Thus, the torque ripples and flux ripples were higher than hysteresis limits and the conventional DTC resulted in large flux and torque ripples. To overcome this issue, the conventional DTC scheme was replaced with the FLC structure. The voltage vector selection of optimal value was achieved by inferring the ranges of torque errors and flux errors. Another FLC was employed into the structure to determine the action time of the vectors. This was obtained by inferring the duty ratio, which was also determined by the second FLC in the structure. Furthermore, the proposed scheme was analyzed and validated using four various parameters like speed, torque, flux and current for both DTC & FLC schemes. Lastly, this control system was elucidated from the analysis that the proposed FLC methodology resulted in smaller ripples at a steady-state than the conventional one and also with quicker dynamic performance. With the proposed method, the torque ripple was almost reduced by 75%, the flux ripple was reduced by 50% and the reduction of fluctuation and stator current. However, the setback with design of FLC scheme was that it required some intuitive understanding of the process. Even though the fluctuations and oscillations in the torque and speed response were reduced, there were some oscillations and fluctuations, which needed to be further reduced.

Sliding Mode Control (SMC) method was considered to be one of the successful non-linear control methodologies owing to its robustness. However, in the case of the non-linear system, some chattering phenomenon was being observed during the process of sliding at the end surfaces. To cope with the chattering phenomenon, a composite technique was studied by H. Wang et al. in 2016 [31]. The studied composite scheme contained Continuous Terminal Sliding Mode Control (CTSMC) with ESO. The CTSMC was employed to cope with the chattering phenomenon. However, in the presence of stronger disturbance in the PMSM system, this would result in steady-state speed fluctuation. To solve this issue, an ESO with adjustable gain was introduced. Besides, this particular study was contributed to the attenuation of the chattering phenomenon along with the speed regulation and disturbance rejection of PMSM. The CTSCM scheme was used as a feedback regulation in order to stabilize the PMSM drive dynamics in a finite time. ESO was employed as feed-forward compensation to regulate the steady-state speed fluctuation of PMSM drive in the presence of disturbance. To validate the proposed methodology, the scheme was implemented with DSP TMS320F2808 with 100MHz clock frequency. Based on the results obtained, it can be seen that the CTSMC had shorter settling time and the overshoot was almost minimal for both CTSMC and SMC schemes. However, with the introduction of sudden load, better disturbance rejection property was observed in the composite mode only. Also, it was inferred that the composite method produced better tracking properties and faster convergence compared to the conventional one. In order to improve the disturbance rejection property of the CTSMC, switching gain was adjusted by varying from smaller to a larger value. The more the value of gain, the better the rejection. On the other hand, speed fluctuation was more for larger gain values. Hence, it was quite complex to achieve a trade-off in rejection of disturbances and minimal speed fluctuation with an adjusting gain. The same analysis was carried out for the composite mode where for a smaller gain, it resulted in good disturbance rejection and small steady-state fluctuations. This was far less than the one by CTSMC with the adjustable gain method. Lastly, it was noted that the speed response of the system with composite mode resulted in some dead time and resulted in more rise time than the other two schemes. It was also observed that the gain parameter had a coupled effect on tracking and disturbance rejection characteristics.

Predictive controllers were the class of optimal control methods that were usually employed if in a case to determine the future behavior of the system. Model Predictive Control (MPC) was such an optimal control scheme and was quite popular in industries because of its capability to forecast the behavior of the system in addition to its control action according to the target optimizing function. A simple and effective Predictive Functional Control (PFC) methodology for PMSM drive to improve its controller performance was proposed by S. Wang et al. in 2015 [32]. According to the authors' explanations, the PFC was majorly employed to overcome the limitations of MPC. MPC involved a higher computational burden since it required optimization at every sampling instant. The PFC was essentially an alternate version of MPC. This is because the PFC retained most of the advantages like handling constraints and online optimization with a low computational cost. The reduction in computational complexity was achieved through more intuitive design procedures. Besides, the speed control of PMSM using a cascade structure was carried out by this methodology. The methodology was a two-level design procedure. In the first level, forecasting of the current values was carried out which was followed by an optimization procedure to optimize the level one value using a suitable cost function. The system performed well for a few well-defined conditions. However, when subjected to strong disturbances, the performance was not quite satisfactory. Hence, Improved Predictive Functional Control (IPFC) was proposed to compensate for unknown dynamics and stronger external perturbations. The proposed IPFC was a composite scheme that employed PFC with ESO. This was utilized for effective controller performance. Feed-forward compensation was provided for better disturbance rejection properties. The entire control algorithm was implemented using DSP TMS320F2808 with 100MHz as clock frequency and the implementation of the control algorithm was carried out using C-language programming. One of the advantages of the PFC is it resulted in minimal overshoot and small settling time compared with PI. During the introduction/removal of load, speed fluctuations were less in PFC. The real-time experimental results also elucidated that PFC provides better disturbance rejection and faster recovery time after the load introduction/removal. To improve disturbance rejection capabilities further, the system was assessed with IPFC where a feed-forward compensation was introduced for better disturbance rejection. This resulted in the smallest settling time and very minimal overshoots than PFC and PI schemes. In addition to that, during the load introduction/removal, faster recovery and very minimal fluctuations were observed. Lastly, in the real-time analysis, PFC + ESO resulted in very good disturbance rejection properties. However, the speed and current waveform of the system contained a lot of oscillations/ripples using the proposed methodology.

Furthermore, C. Dang et al also suggested analysis and reducing methods of cogging torque on permanent magnet AC servo motor in 2014 [33]. According to the authors, the permanent magnet poles unavoidably interacted with armature iron core and hence produced cogging torque that caused vibration and noise, which affected the operation performance and control accuracy of the Motor. The computation techniques for the cogging torque included energy method, the Maxwell tensor method, and the Finite element method. The three predeveloped methods were used to reduce the cogging torque effectively. These methods implied the adjustment of the width of the slots, the use of unequal thickness of the permanent magnets and the use of unequal widths of the permanent magnets. Based on these methods, the finite element method was used to set; a variety of programs were compared and an optimal solution was proposed. Based on the experiments and analysis of this investigation, it was found that the cogging torque was affected by the solder bath placed on the stator. When the stator yoke portion was uniform, it did not affect the magnetic circuit of the stator. After notching the solder bath periodically, the resistance of the circuit got affected. This affected flux density, thereby affecting the air-gap magnetic and this energy was converted into cogging torque. Nevertheless, the cogging torque still was reduced to some extent. It was assured that thickening the stator yoke to reduce the saturation level could reduce the impact of the solder bath and reduce the cogging torque further but it would lead to the reduction of the power density of the motor.

A methodology for reduction of torque ripple for Brushless Direct Current (BLDC) Motor was proposed by optimizing reference current utilizing the Integral Variable Structural Control (IVSC) strategy. This methodology was suggested by C. Xia et al. in their research paper in 2014 [34]. The authors explained that there were two types of commutation modes which were low-speed commutations with and high-speed commutations. The actual type of commutation was determined with respect to the relation between back-EMF (Electromotive force) and voltage of DC links. The commutation controlled by double-phase switching for current optimization of non-commutated windings was used for low-speed commutation. However, if the same was applied for high-speed commutation, the non-commutated line would fail to trace the reference current and would also introduce ripples in the torque response of the system. In order to avoid this, three-phase switching was explored in this work for high-speed commutation instead of double phase switching. Furthermore, the control structure contained two loops. The current optimization was carried out in the inner loop and the respective speed control was carried out in the outer loop using the PI technique. This method involved the estimation of the back-EMF using Luenberger full order state observer. Also, the optimization was carried out in accordance with the back-EMF waveform of both the modes. This proposed scheme was validated in real-time using the DSP TMS320F28335 for surface mounted BLDC system. The stability of IVSC was further analyzed with the Lyapunov candidate function. In short, this method was employed with an IVSC strategy owing to its advantages like robust disturbance rejection capabilities and wider noise band suppression competency. These features were fully utilized, which resulted in the avoidance of a negative chattering phenomenon. The reduction in the torque ripple and the improvement in controller performance over a wider range of load and speed were observed. Lastly, it was noted that the use of three-phase commutation switching action increased the commutation time, cost and also decreased efficiency of the process. However, the methodology played a dominant role in ripple reduction.

The performance comparison of PMSM for the control of speed using Proportional Integral (PI) and FLC schemes was carried out. This study was conducted by S. P. Singh et al. in 2016 [35]. The FLC technique involved the designing of input-output mapping of the controller's behavior which was generally expressed as fuzzy rules. The input to the FLC was a crisp value that would be fuzzified and this value was taken for fuzzy operations. After that, mapping of degree of matching to fuzzy output by suitable implication methodology was carried out. Followed by, aggregation of output and defuzzification mechanism was performed. The output of the FLC was again a crisp value because of the choice of the Fuzzy Inference System (FIS - Mamdani) used for the study. In this study, error and the derivative of error of speed are used as input to FLC. Besides, each input was defined with Seven membership functions with a maximum of 49 rules that were designed for tuning the process. Mamdani type inference mechanism was used as the FIS scheme for the control of speed for the motor drive and the center of gravity method was utilized for the defuzzification process. As a conclusion, the PI scheme was easily affected by non-linear dynamics and time-varying parameters. To cope with that, an intelligent controller using FLC was incorporated. The simulation analysis was performed for various conditions like no-load, full load and varying load scenarios. For no-load condition, the overshoot of PI was 0.38% with settling time of 0.16 seconds, whereas, for full load condition, the overshoot was 0.033% and settling time was 0.034 seconds. Under varying load conditions, the overshoot was 0.6% for PI and 0.053% for FLC with a settling time of 0.16 seconds for PI and 0.04 seconds for FLC respectively. It was inferred from the simulation analysis that FLC outperforms PI scheme owing to its highly adaptable nature. However, the major setback of designing the FLC was that it required knowledge/experience of humans regarding the particular system of interest for which FLC design had to be carried out.

A novel methodology for Active Disturbance Rejection Control (ADRC) for suppressing the overshoots of the highly dynamic input signal was outlined. This proposed scheme is designed by Tianrui Luan et al. in 2016 [36]. The proposed scheme was subjected to an analysis of the PMSM system. ADRC structure encompassed Three sub-components namely TD, ESO and State Error Feedback (SEF) respectively. There were many non-linear parameters associated with the ADRC scheme and these parameters introduced difficulty in tuning. To avoid this and also to obtain speed regulation, a simplified approach was proposed. The proposed approach primarily eliminated the TD component and further linearization was carried out in ESO and SEF components. Hence, this reduced the tuning complexity and also resulted in better dynamic performance and improved robustness to disturbances. Besides, the proposed scheme was a two-step procedure where the primary step was to tune tracing and the disturbance estimation parameter as they were supposed to tune in accordance with each other. The secondary step was to find the optimal tuning parameter of the controller and the settling time was chosen as an objective criterion. The benefits of the proposed scheme are the ADRC possessed smaller rise time and also faster recovery time whenever the load was removed/added when compared with the PI. Next. the rise time was around 0.066 seconds for ADRC whereas, for the PI, it was 0.095 seconds during implementation. The separation principle could be used in ADRC for designing ESO and SEF. It was noted that there was no authenticated mathematical evidence that claimed the design procedure for ADRC parameters. The used method gave only the generalized disturbance estimated by ESO. Plus, the combined expression for dynamic disturbances of both internal and external effects was not used here. However, the torque and speed response contained oscillations and fluctuations.

Apart from that, the experiments on Induction Motor with the objective to develop a digital controller for Induction Motor (IM) Drive was carried out by Y. Zhang et al. in 2013 [37]. The improvement of Field Oriented Control (FOC) for Induction Motor Drive (IMD) was achieved by using the ADRC scheme. The analysis was performed without any Speed Sensor. The implementations of control algorithms were carried out in Digital Signal Processors (DSP) and Field Programmable Gate Array (FPGA) was used for some basic logical manipulations. The concept behind this control strategy was to identify the unknown disturbances using extended observers and to compensate for it in real-time. The Two control algorithms namely ADRC and PID were implemented in DSP processors. The PI parameters were tuned by trial and error method whereas the ADRC was tuned with Linear Extended State Observer (LESO) and it followed the conventional systematic procedure. Moreover, the real-time implementations were carried out with the TMS320F2812 DSP processor and EP2C5T144 FPGA processor. However, the major drawback of FOC which required co-ordinate transformation and current controllers was modified with the ADRC scheme. The analysis showed that the ADRC outperformed the PID scheme without overshoots and oscillations. Lastly, owing to tuning by trial and error, the speed response of the PI controller resulted in larger settling time, rise time and overshoots whereas the ADRC resulted in faster settling and very minimal overshoot. Though, this approach of using DSP and FPGA introduced complexity in design, space and also in cost aspect.

W. Bin et al. conducted a study on the application of control techniques with respect to the region of operation for achieving the full range speed in 2014 [38]. Based on the authors' research, the constant torque and constant power zone were taken for analysis. The Interior Permanent Magnet Motor (IPMM) drive also was taken for study. For the constant power range, in order to keep the Motor with the unchanged power, the Field Weakening (FW) control was applied. Meanwhile, for regions with constant torque, Maximum Torque Per Ampere (MTPA) was applied for full torque performance requirements. When Motor was operating at a constant torque region, the MTPA control scheme was utilized to use the advantage of the torque reluctance of the Motor. When producing constant torque with minimal current, by using this control scheme, Motor efficiency could be highly improved by decreasing the copper loss. On the other hand, if the speed of the Motor was more than the base speed, this would result in the increase of the back-EMF. However, the higher Inverter voltage introduced bounds on the Motor terminal voltage. Therefore, to maintain the balance in voltage level during high-speed rotation, the stator current was manipulated by increasing the demagnetization current. In this scenario, the flux weakening scheme should be used. Furthermore, the important machine parameters based vector control method was obtained through Finite Element Analysis (FEA). For Motor speed below the base speed, the analysis was carried out with two schemes namely control and MTPA control. On the other hand, for Motor speed greater than base speed, the analysis on smooth switching from MTPA to FW was carried out. Based on the analysis, the results showed that the improved dynamic performance was obtained by the appropriate choice of control strategy according to the particular operating region. However, during switching, torque ripples were evident from the study which may have required some ripple suppression techniques to be incorporated with the proposed methodology.

For Motor control, generally high precise and reliable Sensors were required for accurate positioning. However, owing to reasons like space constraint, cost, and system complexity, these Sensors were not installed especially in the case of serious industrial environments. Therefore, sensor-less speed identification was another important area gaining wider attention. Z. Ding et al. proposed another speed control technique for permanent magnet synchronous motor in 2014 [39]. The proposed methodology suggested Sensor-less speed identification and speed control using a Sliding mode approach. The analysis was performed on the PMSM system. The conventional PI scheme was replaced with SMC structure to improve the performance mainly because of the presence of non-linear characteristics associated with the PMSM drive. The speed identification was carried out with variable structure Model Reference Adaptive Control (MRAC) scheme where SMC was integrated with MRAC structure. Also, the MRAC scheme contained an actual model and a reference model. They were compared each time and according to the deviation between them, corresponding control action was carried out with a suitable adaptation mechanism. This scheme also was incorporated with the SMC scheme. The control law was constructed with a sigmoid function. Since the traditional SMC utilized signum function for switching resulted in a chattering phenomenon. Therefore, to overcome this drawback, the signum function was substituted with the sigmoid function. SMC based MRAC was used for speed identification. Furthermore, the proposed structure was validated for the reach-ability condition using the Lyapunov analysis. The SMC function was designed with the variable exponential rate reaching law for quicker sliding and for the elimination of chattering effect. For the proposed structure, Lyapunov analysis was carried out for stability assurance. In short, this proposed method was elucidated that the estimated speed was tracked quickly and properly. It was inferred that the SMC scheme resulted in faster response, lesser speed overshoots and high robustness. However, the precise performance largely depended on the reference model used in the structure. Also, the system torque and speed response contained oscillations and fluctuations

It was highly challenging for the system performance to be robust when the system was subjected to unknown disturbances and uncertainties in the parameters unless the system was employed with more sophisticated control algorithms. To cope with the time-varying parametric uncertainties and perturbations, non-linear control techniques were largely adopted to improve the performance of the system. The SMC was one of the non-linear robust strategy employed in many fields because of its advantages like easy tuning and implementation for highly non-linear systems. However, the system would be associated with some chattering phenomenon because of its discontinuous switching action. To compensate for disturbances, an observer could be introduced and based on this effect, switching gain had to be selected appropriately to minimize the chattering. Apart from the above-discussed method, the chattering phenomenon along with time-varying uncertainties was also addressed with other composite schemes. Therefore, Generalized Proportional Integral (GPI) observer with SCM (GPI+SCM) for better rejection of disturbances and unknown uncertainties of the system were proposed by H. Wang et al [40]. The proposed methodology was tested for speed regulation of the PMSM drive. The procedure involved the design of the GPI observer for disturbance rejection and SMC for speed regulation. The GPI observer for PMSM drive was designed as a function of external perturbations, frictional loads and current tracking error. The final gain parameter tuning was obtained as the function of the single parameter by directly equating to the characteristic polynomial of the observer using a direct comparison method by assuming that poles were in complex left half far away from the imaginary axis. Besides, the speed control regulation was achieved by combining SMC with GPI observer. It was stated that convergence of the speed error to equilibrium point asymptotically was assured if the switching gain was larger than the gain of the disturbance error estimation parameter. In addition, SMC did not require rejecting disturbance with feed-forward compensation using a disturbance estimator. As a conclusion, both the schemes possess minimal overshoot with small settling time. However, for the application of constant load torque, it was inferred that speed recovery in the composite scheme was faster than the SMC. The composite method could estimate and reject ramp disturbances. When the slowly varying signal was applied with a sufficiently larger gain for SMC, it was difficult to suppress the disturbance. However, the composite mode rejected in a better way with much smaller gain value. Lastly, during the recovery/rejection, some overshoots and oscillations (in case of ramp signal) were observed in the speed regulation performance, which may have needed to be further addressed.

Besides that, the SMC also was widely adopted in most of the highly non-linear electromechanical systems owing to its highly remarkable features such as excellent tracking properties and robustness for disturbance rejection and time-varying parameters of the system. However, some of the chattering phenomena were observed because of the discontinuous switching whose again could be reduced by adjusting switching gain parameters. Even the highly sophisticated control algorithms might have performance degradation if in case a fault associated with any Actuator or Sensor components of the system. To overcome this issue, many fault diagnostic approaches were developed in recent trends. The Fault Tolerant Control (FTC) approach using the SMC strategy for PMSM Drives had been studied by H. Mekki et al. in 2015 [41]. The fault associated with stator asymmetries had been addressed in this research. The healthy model of PMSM was applied with an integral surface SMC strategy. The surface integral SMC for PMSM drive was provided with Three surfaces, utilized for speed, direct and quadrature current regulators. The proposed scheme was analyzed for closed-loop stability performance with Lyapunov stability studies. The faulty model for eccentric fault diagnosis of PMSM drive was developed. The objective was to make the system to provide continued better performance, even if in case the fault was being identified during the process such that reconfiguration was not required during the process. Furthermore, to improve the controller performance under faulty conditions, the internal switching SMC scheme was reinforced with the FTC approach. Lastly, the Lyapunov stability analysis was carried out for the FTC approach and also for continued stable performance [41]. In short, this novel SMC provided good robust tracking properties. However, in the presence of static stator fault, the performance was degraded largely. The FTC with SMC resulted in good reference tracking and rejection of load disturbance even when the system was subjected to eccentricity faults. It was inferred that the system possessed faster dynamic performance and it was highly robust under faulty conditions. However, systems speed and current responses contained oscillations and fluctuations under stator faults and needed to be further improved.

The PFC accuracy was largely dependent on its external perturbations. This had been addressed with a composite scheme like PFC+ESO and the performance was improved. However, apart from the external disturbances, speed feedback quantization error also largely influenced the performance of the system. A methodology for better dynamic performance was proposed with PFC by incorporating a Kalman filter (KF). This methodology was investigated and suggested by H. Liu and S. Li in 2012 [42]. By employing the Kalman filter, a better estimation of states was made possible by eliminating system and measurement noise. KF was mainly used to obtain the information of load torque, position of the rotor and the speed. Its ability to operate in a noisy environment (both system's and measurement noise) and also the disturbance estimation resulted in better performance. Besides, the PFC is the modified version of MPC with minimal computational complexity. It also contained some base function in terms of control variable of interest and it is a predictive model. Plus, it contained some amount of error correction phenomenon between predicted and the actual model. The receding optimization control methodology with the objective to minimize the variance employed with quadratic cost functions. This approach was added with the KF for compensation of quantization errors in speed feedback loop mainly because of rotor precision limitations. The estimated and validated information were used in the PFC control scheme for performance enhancement of the system. The proposed scheme was implemented in real-time using Infineon's XMC4500, 120 MHz clock CPU frequency of ARM Cortes core. Incremental Photo Encoders were used for rotor position detection. It can be concluded that both schemes were stable and could detect speed changes. However, there was lag associated with detection by M/T method (measuring both frequency and time speed method) and also its tracking performance was not as accurate as compared to the KF method. Secondly, observer performance analysis was carried out with Disturbance Observer-Based (DOB) method. For changes in load torque, the DOB method introduced some overshoots and it converged within 0.3 seconds. Meanwhile, KF was being stable within 0.15 seconds and the overshoot was comparatively much lesser than the DOB method. Besides, it was observed that dynamic properties of PFC+KF outperform PI with less rise time, settling time and minimal overshoots. The steady-state ripples, overshoots and settling time were more in PI, less in PFC and relatively minimal in PFC+KF scheme. Compared to PFC, PFC+KF possessed a small speed drop and faster recovery time. This was made possible by KF, which helped in creating a better estimation of information for PFC and high-efficiency performance. However, the system speed and current waveforms contained a lot of oscillations and ripples under all of these implemented control methods.

Furthermore, an adaptive control technique was widely preferred in cases where the system was expected to adapt to the changing process parameters/environmental conditions experienced during the processes. According to the research conducted by X. Li and S. Li, Speed loop control for PMSM using adaptive control were initiated [43]. The Model Reference Adaptive Control (MRAC) scheme was employed for the system to accommodate the parameter changes. MRAC scheme consisted of three main components namely, reference model, adaptation mechanism and the controller. The reference model was generally chosen as to how the system was expected to behave. Meanwhile, the adaptation mechanism was about how the system had to accommodate to the changes and at what rate the system had to be adapted like the reference model and also to account for perturbations. Thirdly, the controller was the basic control structure or control law, which was usually employed in the system. Every time, the deviation between the plant model and the reference model was accounted for. Based on the deviation, according to the adaptation mechanism, corresponding control actions were provided each time. Also, the control performance was quite improved and the adaption mechanism was carried by using Lyapunov stability analysis by the appropriate choice of candidate function. However, to improve the disturbance rejection capabilities, the system was incorporated with ESO to compensate for uncertainties and unknown dynamics. The stability analysis was carried for the composite method. The proposed scheme was implemented using DSP TMS320F2808 with a clock frequency of 100MHz and C-programming language was used to implement the control algorithm. In short, the MRAC resulted in better performance than PI in a relative way in terms of fewer overshoots and steady-state oscillations. MRAC had a good dynamic load performance. It resulted in a smoother response and very minimal overshoot. Even in the presence of the load torque disturbances, MRAC performed better than PI. However, for better rejection, feed-forward compensation was employed by introducing an observer. The composite structure resulted in better properties than MRAC with relatively less settling time and overshoots. Furthermore, the composite scheme resulted in very good disturbance rejection properties with very short recovery time. This composite MRAC (MRAC+ESO) scheme possessed improved controller performance with high robustness. It was also to be noted that the composite method degraded the adaptation capability of the system. This was mainly evident from the steady-state ripple which was always greater than the MRAC scheme.

Apart from the handling of parameter variation and the unknown dynamics of the system by adaptive structures, for enhancing the performance of the closed-loop, a fractional adaptation mechanism was developed. The MRAC using factional adaptive scheme was utilized in the PMSM drive for velocity control. Two mechanisms of adaptation were elaborated in this work. The mechanisms were a gradient-based fractional order adaptation scheme and Lyapunov based fractional order adaptation scheme. It was inferred that for the gradient-based adaptation approach that convergence of the system could be increased by increasing the adaptation rate (γ). However, In the Lyapunov adaptation mechanism, it was inferred that larger the γ, slower the adaptation rate. Larger α was better for the transient response and disturbance rejection features. These results were completely contradictory to the gradient-based adaptation method. Apart from that, the presence of oscillations in the transient response also was observed. To overcome this oscillatory behavior, the normalized gradient approach had to be introduced. The methodology for velocity control of the PMSM system consisted of two loops. The inner loop controlled by feedback linearization to obtain the reference voltage information and the outer loop employed with Reference Signal Tracking (RST) scheme for current information. Also, the outer loop control parameters were tuned by a fractional adaptive mechanism using the MRAC technique. Moreover, Lyapunov analysis was carried out for the design of the fractional-order MRAC scheme. Besides, the stator reference current parameters were controlled with the RST scheme. The parameters of RST were adapted periodically using the gradient-based approach or Lyapunov adaptation with MRAC structure. The stator reference voltages were compensated with a feedback linearization mechanism. It should be noted that the reference model time constant had to be always greater than the time constant of the inner loop to preserve the system dynamics [44]. As a conclusion, to demonstrate the robustness of the system, parameter uncertainty was tested by varying inertia to +30% for both the approaches. The responses did not introduce any compromise in the performance. Better transient response was achieved at lower in case of gradient approach whereas, for the later, the system performed well with large values of α. Secondly, the proposed scheme was compared with the adaptive backstepping algorithm. It was inferred that the proposed FO+MRAC scheme had a higher tendency to cope with mechanical uncertainties and to reject disturbances in an effective way than the later. However, the appropriate choice of fractional order derivative had to be provided with some guidelines to improve the closed-loop performance.

Within real complex industrial situations, handling of disturbances by non-linear systems was quite challenging. Many disturbance rejection techniques were employed to cope with slow varying signal or periodic disturbances. A methodology to reject multiple disturbances using the IMC principle had been identified. This methodology was suggested in the study conducted by Y. Tan et al. in 2015 [45]. The authors proposed the composite control technique which contained a disturbance model being embedded into the disturbance observer for better rejection. This composite model was called as Internal Model Extended State Observer (IMESO), which was employed to reject multiple disturbances. Despite many observer schemes, the reason for the choice of ESO was that the design of the observer by this method required very limited information such as the order of the system, the inputs, and the outputs. The study and the analysis were carried out on the PMSM drive for speed loop under multiple disturbance conditions. Both the simulation and experimentation were carried out for the Three cases namely, proportional feedback with ESO (P+ESO), Proportional feedback with IMESO (P+IMESO) and PI scheme. For the torque ripple information, the obtained speed response of PI was analyzed with Fast Fourier Transform (FFT) to characterize the corresponding harmonics before the experiments. The experiment was carried out for the reference speed of 1500rpm. The proposed scheme was implemented in real-time using the DSPTMS320F2808 processor with associated Power modules. Based on the experimental results, it is elucidated that the P+IMESO performs better with multiple disturbance rejection than the other two schemes. However, the equivalent performance was being observed in the case of time-domain properties. All these schemes possessed small settling time and very minimal overshoot. Also, it was inferred that the proposed scheme had a smaller settling time and little overshoot. The speed ripples observed during the process were small for P+IMESO, which was approximately 2.10 rpm, large for P+ESO and larger for PI schemes during the disturbance rejection of periodic ones. Lastly, the proposed scheme eliminated slowly varying signal and sinusoidal signals effectively. The results elucidated the fact that the proposed methodology (P+IMESO) was capable to reject multiple disturbances and the unknown dynamics associated with the process. However, overshoots during load torque addition/removal could be reduced for performance enhancement.

Apart from that, the tuning of Integer Order PID schemes was usually carried out by using either frequency or time domain specifications. To facilitate the tuning of the FO-PID controller, a graphical approach had been discussed to achieve the robust behavior of the system. FO-PID (Fractional Order PID) consists of Three gains as same as the IO-PID (Integral Order PID). In addition to that, Integral Order (λ) and derivative order (μ). FO-PID became IO-PID if $\lambda = \mu = 1$, even though, FO-PID resulted in more flexibility and improved performance, the tuning was quite complex. The gains of FO-PID were determined by using the D-composition method chosen from the left half of the complex plane, and the degree of stability was defined with a parameter σ. The graphical approach elucidated that the stabilizing region was obtained by the D-decomposition technique by analyzing Three regions of operation namely, Infinite Root Boundary (IRB) lines, Complex Root Boundary (CRB) curves and Real Root Boundary (RRB) curves. The D-composition was obtained by dividing the interval into Three zones, namely at 0, (0, +∞), and +∞ corresponding to each region. The procedure was mainly carried out to reduce the complexity involved in fractional order PID tuning. The validation of the proposed scheme was performed in real-time for the PMSM drive. The DSP56F8346 was the module used for control in this study [46]. In short, both the schemes were analyzed for Servo and the regulatory properties. It was observed that tracking of step signal by FO-PID was faster compared to IO-PID, and both the schemes resulted in no overshoots. For regulatory conditions, load torque had been changed abruptly. It was observed that FO-PID had a faster recovery to maintain tracking with smaller undershoots than IO-PID. Thus, the experimentation elucidated the robust behavior of fractional order PID in terms of the dynamic performance produced relatively faster rise time and better disturbance rejection. Even though the graphical tuning method was proposed, assurance of optimal stability value had to be explored.

Besides that, the popularity of PI controllers in industries was mainly because of its simplicity and effectiveness for the reasonable performance of the system. PMSM drives generally employ the FOC algorithm, which basically involved some transformations to bring the current parameter to the required form (from AC to DC). However, this process was quite time-consuming and used lots of memory. To overcome this, Simplified Vector Control (SVC) had been proposed by W. K. Wibowo and S. Jeong in 2013 [47]. The SVC algorithm was obtained from the inverse of the coordinate transformations used in FOC. Three PI controllers were used in the PMSM control structure. Two corresponds to current and one for speed. These PI were tuned with a heuristic-based optimization algorithm known as the Genetic Algorithm (GA) to obtain optimal tuning parameters for each of the three controllers. Besides, the GA was a local search algorithm originated by the concept of the survival of the fittest. The algorithm had three steps namely selection, crossover and mutation. The potential candidates were selected for the process from the initially generated solutions. They were taken for reproduction either by using two parents (crossover) or by a single parent (mutation). The Mean Square Error (MSE) was used as an objective function and some constraints with respect to the specifications in the time domain such as overshoot, rise time and settling time were provided to the system. After a suitable number of iterations, the algorithm resulted in a solution satisfying both the objective and the constraints imposed on it. Furthermore, the proposed scheme was analyzed for implementation using simulation. The analysis elucidated the fact that the proposed scheme was feasible for environmental conditions where no higher sophistication and precision were required. The tracking of reference speed, response tracking for varying speed and load rejection were all analyzed. Also, it was elucidated that the performance of the system satisfied the requirements stated. The overshoot was 0.41%, settling time was 0.3 seconds and the rise time was 0.37 seconds. The algorithm reflected fairly precise control and could be easily realizable in Microprocessors because of its handle-able sampling time based on the Nyquist sampling criterion. Lastly, the algorithm resulted in a sub-optimal solution since it was a local search algorithm.

Last but not least, although the heuristic-based approaches like GA and Particle Swarm Optimization (PSO) tuned PI controllers gave a better performance than conventional PI, owing to the converge of parameters in sub-optimal level, the performance efficiency still hindered. To overcome this, the algorithm, which resulted in global optimal was taken for analysis. R. Kannan et al chose a Bio-geographical based optimization (BBO) for the tuning of parameters for PI controller [48]. BBO was the algorithm that was inspired as the collection of biological distribution of species from the geological area. The objective was to minimize the difference between actual and the reference speed of the PMSM drive. Habitat Sustainability Index (HSI) was mostly used for determining the optimal solution in BBO. The value was high in favorable regions and low in the case of unfavorable regions. Moreover, the migrations were also possible into or out of the regions, namely, emigration or immigration. So, HSI was improved largely by migration phenomenon. After several trials, solution convergence was attained. For the converged parameters, the controller was tested for real-time performance. Apart from that, the parameters obtained through Zeigler Nicolas (Zn), Real Coded Genetic Algorithm (RGA), and BBO were tested for different scenarios like no-load, full load, and disturbance rejection conditions. The tuning of PI parameters was carried out offline. The several performance measures, namely Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), Integral Square Error (ISE), and Integral Time Square Error (ITSE) had been evaluated for all the three schemes. It was inferred that the BBO tuned controller reduced steady-state error up to 75.2% and transient error up to 52%. However, for even better performance, swarm-based optimization techniques could be employed.

2.4 AC SERVOMOTOR CONTROL TECHNIQUES COMPARISON

All of the available control techniques for the AC Servomotor were compared in terms of their advantages and disadvantages, as shown in Table 2.1 below. The precise control of speed, position, and torque were the main issues with the AC Servomotor. Many control techniques and algorithms such as neural networks, fuzzy logic, iterative control, vector control, scalar control, electronic power drives, repetitive control, PLC control, internal model control, current differential signals control, digital signal processing, FPGA, sliding mode control, continuous path tracking, direct torque control, predictive functional control, and active disturbance rejection control were implemented for the solution of these issues. However, all of the above-stated control techniques had their advantages and limitations. Most of these control techniques led to the step response issues, waveform oscillatory errors and fluctuations, instability of the system, switching losses, sensitivity to parameter variations and external disturbances, and low dynamic responses. Each control technique led to at least two of the issues mentioned above. There was no control technique implemented that could solve all of these issues at the same time while offering a high precision control

Control	**Control Technique**	**Advantages**	**Disadvantages**
Position	Continues path tracking [2]	Good step response	Dynamic load issues and more energy consumption
	Repetitive control [3]	Robustness against noises, unaffected by load variations and more stable	Step response issues, position tracking error
	Enhanced Iterative Learning [4]	Robustness against noises	Position tracking error and dynamic load issues
	Internal Model [5]	Good performance and low tracking error	Step response issues and dynamic load issues
	Robust tracking [6]	Good dynamic load response	Step response issues tracking error, network framework and fault tolerance issues
Speed	Fuzzy logic [7]	Good dynamic load response, small switching losses and minimize chattering	Existence of viscous friction and step response issues, rotor time constant is unknown, heavy parameter variations
	Vector-based speed control [8]	Good step response	Dynamic load issues
	Low-speed control [9]	Good control on the regulation of the motor speed	Fluctuation and oscillatory errors in the speed response
	Current differential signals [10]	Reduction of copper losses, improvement in inverter voltage utilization	Waveforms Oscillatory errors and voltage saturation
	Active Disturbance Rejection [11]	The ability of unknown errors compression and good step response	Improvement needed in speed response and dynamic speed response
	Fuzzy Logic [12]	Highly adaptive, good tracking performance and robustness	Fluctuations and oscillatory errors
	Decoupled ADRC for PMSM drives [13]	Independency of the system parameters and easy tuning of the controller	Oscillations are evident in both speed and current responses
Position,Speed and Torque	Neural Networks [14]	Good dynamic load response, no overshoot and oscillatory errors	System response is slow, high rise time
	Variable Structure Direct Adaptive [15]	Good dynamic load response	Presence of chattering and step response issues
	Iterative learning [16]	Fluctuations in the waveforms are eliminated	The elimination of fluctuations takes few cycles that may affect the current response
	Vector control using custom-designed motion control card [17]	Good dynamic load response	Oscillatory errors and fluctuations
	XC164CM Microcontroller [18]	Simplified hardware design and good reliability	Presence of oscillatory errors
	PLC [19]	Good performance and low THD level at high speed	Fluctuations in the step response of the system and high THD level at low speed
	Multi-layer Neural Network [20]	Good dynamic load response	Delay and overshoot in the speed response
	Fuzzy Adaptive PID [21]	Good position and speed control	Fluctuations in the system frequency and the rise time of the speed response is high
	Current control using the DC-link current sensor [22]	Good system response	Electrical parameters variation in practical
	Single-chip motion control IC [23]	Fast response and good dynamic load response, The IC can be easily tuned to be used for different motors	Oscillatory errors in the step response of the torque and the voltage switching waveforms
	Sensor-less servo control system [24]	Robustness against harsh environment such as underwater usage	Amplitude error between the real speed and reference speed and oscillatory errors in the system response
	The full closed-loop control system of Gear Measuring Centre [25]	Good system performance and robustness against the variations of the system components	More expensive, complex, risk of instability and oscillatory errors
	Automatic control loop tuning [26]	Good dynamic load response	Presence of oscillatory errors and error in the parameter auto-identification
	STM32 Microcontroller [27]	Strong real-time performance, reliable operation and static precision	Dynamic load issue
	Optimized control of servo-motor drives in the field weakening region [28]	Robustness against parameters variations	More complex, its voltage and current waveforms contain oscillations, which may affect the performance of the system

	Direct Torque Control based FLC [29]	Reduction in torque ripple and flux ripple, good dynamic response	Oscillatory errors and fluctuations in the waveforms
	Continuous Terminal Sliding Mode with Extended State Observer [30]	Small steady-state response and disturbance rejection	Speed response leads to dead time and high-rise time, effects of gain parameters on the system performance
	Predictive Functional Control with Kalman Filter [31]	Good dynamic performance and fast recovery time	Oscillatory error and ripples in the system waveforms

3. CONCLUSION

A general review on the control of the AC Servomotor was done; this review was taken from the research articles and the research papers that were published for the control of the AC Servomotor. It covered all of the commercially available control methods for the AC Servomotor, which include control of speed, torque and position of the AC Servomotor. Matlab Simulink, C programming, and Programmable Logic Controller (PLC) programming were used in the implementation of these control approaches. The advantages and drawbacks of these control strategies were discussed and compared in this review. This review was analyzed and related to the industrial application to investigate the most demanded solutions of the problems by the industry. From the analysis, it was obtained that it is a necessity in the industry to precisely control the position, speed and torque of the AC Servomotor when handling a dynamic load; however, such a precise control method has not been designed yet.

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