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Review of RDC Soft Computing Techniques for Accurate Measurement of Resolver Rotor Angle

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Abstract: A resolver is a position sensor or transducer that measures the instantaneous angular position of the rotating shaft to which it is attached. Resolver produces two amplitude modulated signals; SIN and COS as output signals. These two signals need to be demodulated and converted to digital signals before they can be used for control. There are several techniques available in the literature to measure the rotor shaft angle. This paper focuses on the design of both hardware and software based resolver to digital converter (RDC) techniques available in the literature. This literature review helps the researchers to know about all these methods and plan future work on RDCs to improve the angle tracking performance. *Copyright © 2013 IFSA.*

Keywords: Resolver, Resolver to digital converter, Angle tracking observer, Inverse tangent method.

1. Introduction

Every machine, process and monitoring system has a rotating shaft in its mechanism. One of the critical point for the motion control system is to determine the rotor angular position accurately in order to enable its control and allow phase inversions at the right time. The accuracy of the angular position influences the system efficiency, but also the torque control for optimum driving sensation. Such angle sensors need to be able to work in harsh environments, be accurate, safe and reliable. Machine tool and robotics manufacturers use resolvers and synchros to provide accurate angular and rotational information. These devices excel in demanding factory and aviation applications requiring small size, long term reliability, absolute position measurement, high accuracy, and low noise operation. Resolvers are extensively used in applications that demand instantaneous, accurate and high resolution information angular position or speed. A resolver's analog outputs have been modulated by rotor excitation signal and Resolver to digital converter (RDC) is always adopted to recover the angular position in digital form. RDCs are widely used in automotive and industrial applications to provide motor shaft position and/or velocity feedback. RDC performs two basic functions: demodulation of the resolver signals to remove the carrier, and angle determination to provide a digital representation of the rotor angle. All RDC techniques use the two analog signals to produce a digital output. The differences between the various converter methods is in the resolution available, the speed at which the shaft can be rotated, the designed resolution and the sensitivity of the system to the unwanted distortion of the resolver signals [1]. The main drawback of RDC is its cost, which is about the same price as that of the resolver [2, 3]. Recently, researchers have paid attention on RDCs with soft computing techniques to improve the linearity, resolution and accuracy of the rotor shaft angle of the resolver.

2. RDC Techniques

John Pezzlo and Chong Loh Tsiang [4] discussed the disadvantages and deficiencies to measure the angular position using contacting transducers and presented a design method to overcome the disadvantages by providing a novel non-contacting method. According to this design, the resolver is operated in a phase shift mode whereby the alternating current output voltage is constant and the phase of the output signal with respect to a reference varies in direct proportional to the shaft position of interest. Robert M. Kay [5] developed a simple structure for RDC based on phase locked loop using analog electronic hardware. This method converts a predefined frequency signal to a given waveform sequence by an electronic logic circuit, band pass filtered and phase splitted into orthogonal components. This method reduces the system components by 90 %.

George W. Miller and Larry A. Meyer [6] proposed an RDC circuit to provide the accurate control of the resolver stator winding excitation signal using digital signals. The proposed design method improves the accuracy of the digital output. Richard W. Cording and Daniel D. Morton [7] designed an electronic circuit to measure the angular position of a rotatable device that has the capability of recognizing the fault conditions of the resolver. The designed circuit provides a digital output that can be directly interfaced with a microprocessor control unit. Control logic and fault detection logic are provided in the proposed design to measure the periodic angle of a plurality of rotatable device and to provide the erroneous angle indications in a resolver respectively. Edward L. Denham and Michael J. Tuso [8] proposed the design of a resolver control system to provide the feedback information to monitor the position of a controlled machine and to measure the true monitored position continuously. The developed system compensates the output value of resolver position detection from systematic phase errors. Peter G. Serev and Roger M. Bogin [9] developed a microcomputer control system for sensing the shaft angle of a resolver and controlling the programmable limit switches using resolver to digital angle converter. Tadahiro Ono [10] proposed a resolver type rotational positioning arrangement system to provide an improved resolution without resorting to increasing clock pulse frequency.

The design of highly accurate, high resolution multiple self corrected synchro/resolver presented by Ross D. Wellburn and Santa Rosa [11]. This design requires minimal maintenance, very much immune to distortions and it can also be used as an independent positioning device. James A. Blackburn *et al.* [12] experimented on a driven damped pendulum to observe the range of dynamical modes and presented a state diagram for the system. The pendulum coordinate was measured with an angular resolver, in combination with an integrated RDC with fourteen bit precision. The presented experimental results emphasized that this constitutes a direct and accurate measurement of chaos in a real physical system. Peter G. Serev [13] developed a microcontroller based RDC with synchronous sample and hold demodulator. This method optimizes the time taken for the sample and hold circuit and minimizes the quadrature and even harmonic effects in the resolver output. The shaft angle of the resolver was extracted using digital signal processing techniques. Duane Hanselman [14-16] has analyzed the effects of the most common non-ideal resolver signal characteristics on the position accuracy using RDC.

The proposed RDC is based on tracking algorithm. The expressions for angular position accuracy due to inductive harmonics, inductive DC component feed through, quadrature error, amplitude imbalance, and imperfection quadrature component rejection were developed. Various methods for reducing the position error caused by the existence of non-ideal resolver signal characteristics are presented by Duane Hanselman [16]. Yasuhiro Ezuka [17] described that an RDC with high accuracy can be achieved if tracking type signal processing technique is employed. Different techniques to reduce the position error caused by existence of resolver signal characteristics are discussed by Duane Hanselman [18]. This paper introduced a signal processing technique to eliminate the position error particularly due to resolver quadrature imperfection. The proposed method eliminates the quadrature error by simple algebraic manipulation of resolver signals. The paper also showed that all the even harmonics in the resolver signals can be cancelled if the resolver was constructed with complementary phases. Choong Hyuk Yim *et al.* [19] proposed a fast tracking method for RDC with a bang-bang type phase comparator. To reject carrier signal and noise, the proposed method replaces the low pass filter with two pre filters outside the RDC. Bruce N. Eyerly and Donald R. Cargille [20] invented a phase compensation circuit to compensate resolver angle measurement error without the use of special compensation windings on the resolver. The proposed invention provides increased accuracy and reduced circuit complexity.

B. A. Murray and W. D. Li [21] designed RDC using TMS320C14 digital signal processor to provide absolute angular position and velocity information for digital servo control systems. The converter algorithm and the error calculation hardware were also developed. The demodulation and error calculation functions were performed in hardware to optimize the low speed performance of the system. Donald K. Taylor *et al.* [22] invented a device and method for recording the position reached by a moving part moved by a rotary shaft in a resolver and tracks the position of a group of servomotors during power down conditions. The proposed method provides for avoiding false motion conditions in detecting motion. According to the method, when a failure in the external power supply occurs, the proposed system was activated automatically without any loss of resolver position information. Dong Il Kim and Jin Won Lee [23] developed fuzzy based control algorithm to estimate the absolute rotor position of the permanent magnet AC servo motor with an incremental encoder coupled to the shaft. The proposed algorithm also enables the servo motor with incremental encoder always controlled with maximum generated torque per ampere of stator current without pulsation. Dean C. Alhorn [24] designed digital IC based multi phase resolver converter used with angular resolver system. The alternative versions that employ incremental or absolute encoders were also discussed. David T. Robinson [25] proposed a low cost design method for inductive transducer to measure absolute position of ac and brushless DC servomotors as well as flux vector control of ac induction motors.

L. Harnefors [26] presented a Kalman filter method for estimation of the rotor speed of an ac motor. This design was based on trigonometric operation and was implemented on a digital signal processor. The performance of the system was validated both in simulation and hardware. Saso P. Vlahu [27] proposed a direct RDC based on tangent algorithm to obtain the angular position of the shaft. The tangent values were converted to linear values using an eight bit look up table. Martin Piedl *et al.* [28] designed digital signal processor based a low cost resolver system to provide close loop motor velocity and position. The paper also discussed the ability to use the system to generate closed loop motor position and/or velocity control of both brushless motors and motors which use commutating brushes. Sheng Ming Yang and Shuenn Jenn Ke [29] presented accurate velocity estimation method for servo motor drives. The performance of the proposed method was investigated by both analysis and experiments and at normal and very low speeds. The quantization error in the velocity feedback signal can be reduced when a closed loop observer is used instead of a backward difference to estimate the motor velocity.

Lennart Harnefors and Hans Peter Nee [30] designed and analyzed an efficient speed and position algorithm applicable to ac motor drives. The algorithm has dynamics corresponding to a phase locked loop and ideally stable. TMS320F240 DSP solution for obtaining the angular position and speed of a resolver was presented by Martin Staebler [31]. This method utilized the under sampling and an inverse tangent algorithm to decode the resolver output signals and oversampling technique was added to achieve high angular resolution. George Ellis and Jens Ohno Krah [32] addressed the tracking loop technique used to measure the position of the rotor shaft of a resolver which causes phase lag between the actual and measured positions. This paper also discussed the problem of phase lag that causes instability in the control loop and reduces the performance of the servo system. The paper concludes the methods to reduce the problems with mechanical resonance and improvement of the dynamic stiffness of the control system. The design of surface micro-machined rotations sensor for angular position detection was presented by Winston Sun and Wen J. Li [33]. The sensor was designed to detect the angular position of a rotating element by measuring the resistance change due to stress induced by centrifugal force on the seismic mass using piezoresistive effects. A wireless transmission scheme for the rotation sensing system was also evaluated.

Sung Jun Park *et al.* [34, 38] proposed a low cost linear encoder suitable for switched reluctance motor (SRM) and also presented a control algorithm to generate switching signals using a simple digital logic. Full implementation of a low cost RDC on a combined analog and digital board was presented by C. Attaianese *et al.* [35]. The experimental results were presented and a comparison with the performances achieved by means of an incremental encoder. George Ellis and Jens Ohno Krah [36] outlined the procedure to reduce the phase lag caused by sensors using observers and RDCs. This paper explained the advantages of RDCs over observers that include providing position and velocity feedback with little or no phase lag, and estimations of motor acceleration and torque disturbance. Aengus Murray *et al.* [37] introduced the design of a high resolution position sensing system, variable reluctance resolver and RDC integrated circuit. The new resolver position sensing system addressed both the cost issues and reliability issues associated with safety automotive applications. The fault detection systems meet the requirements of safety automotive systems.

The design of a low cost software based tracking RDC was proposed by A. O. Di Tommaso and R. Miceli [39]. The comparison between the proposed RDC and a commercial encoder was also presented. The software approach makes no parameter variations due to component drifts, temperature variations, etc. and the output signals result quite immune to noise and to external electromagnetic disturbances. Mohieddine Benammar *et al.* [40] described a new scheme for the measurement of mechanical angle of a RDC. The proposed converter produces an output voltage proportional to the shaft angle by using a linear technique. The converter was implemented using analog circuitry. A design method was proposed by Andreas Bunte and Stephan Beineke [41] to suppress systematic errors of resolvers and optical encoders with sinusoidal line signals. Though the proposed method does not require any additional hardware, the dynamics of the speed control was not affected and it will not cause any time delay. A fundamental impact of the speed measurement system and the dynamic behaviour of modern servo controlled drives are also presented. N. Nowlin *et al.* [42] designed a radiation hardened high precision RDC. The designed RDC has a maximum of 16 bits precision and was manufactured in a total dose hardened 0.6μm CMOS process. Single event latch up and dose rate latch up hardening were designed using guard rings and DICE latches.

L. Z. Sun *et al.* [43] presented a new structure of variable reluctance resolver for integration with motor systems. The proposed resolver directly utilized the salient pole effects with only simple winding patterns on the stator. Based on the theoretical analysis, it is concluded that the errors were mainly caused by the third harmonics and non-effective EMFs existing in the signals. A RDC system was designed that is capable of outputting a good resolver signals without being affected by the motor speed and switching noise was presented by A. Balkovoy and E. Kallenbach [44]. The proposed design was validated through experimental setup. The processed resolver data was compared with the incremental encoder data to estimate the accuracy of the position measurement. Don Payne [45] presented and described the analysis method of accurately measuring a reference position at high rpm engine. The paper also explained the construction and operation of a measurement system to enable convenient determination of angle position. An RDC was described for the linearization of the sine and cosine signals to enable the angle to be determined using simple linear equations was presented by Mohd. A. Avlamadi *et al.* [46]. The converter was implemented using analog electronic circuitry and the practical performance of the converter was also evaluated using PC based test rig.

Victor D. Aksenenko and Sergey I. Matveyev [47] suggested and discussed two approaches for self calibration of digital angle sensors based on integration of two conversion channels with the errors. The methods for determining the rotary angle orientation of a motor using resolver signal were described by Robert Herb [48]. This proposed method utilized a single control system that is arranged both for triggering and for evaluating the resolver signal. A solution for obtaining the estimations of actual angle and speed of the resolver was described by Freescale semiconductors [49]. A theoretical analysis and proposal of the RDC hardware interface and a design of the device software driver were also explained. Mohieddine Benammar *et al.* [50] presented the design of RDC that provides pseudo linear voltage proportional to the shaft angle. The proposed converter was based on the concept of absolute values of the resolver demodulated signal together with a dedicated linearization technique. The converter was implemented using an analogue circuitry.

Gabriel Gross *et al.* [51] implemented an accurate and fast tracking all digital RDC using oversampling and frequency shifting technique along with synchronous rotating reference frame based phase locked loop. The frequency shifting technique was used to demodulate the incoming signals. The input signals were oversampled 32 times to increase their resolution. The proposed system was implemented in a 16 bit digital signal processor. Masayuki Katakura *et al.* [52] have developed a 12-bit RDC with LSI complex twin PLL architecture that tracks a mechanical angle offset by the carrier frequency. The proposed architecture works based on analog oriented mixed signal processing technique. Lizhi Sun *et al.* [53] presented the realization of a new variable reluctance resolver by varying air gap reluctance in certain waveform. The proposed resolver was one type of rotor position sensor for the inverter driven motors. This resolver was designed into compact size and was suitably integrated into Permanent Magnet Synchronous Motor (PMSM) or brushless motors.

A novel hybrid design method for angle tracking observer with a combination of closed loop LTI observer and quadrature encoder was introduced by Reza Hoseinnezhad and Peter Harding [54] and Reza Hoseinnezhad [55]. Finite gain stability of this hybrid design was proved based on circle theorem and the simulation studies comprised two cases where an LTI-ATO and an extended Kalman filter were unstable due to high acceleration and speed. The proposed observer was stable with finite tracking errors. Yoshi Ishizuka *et al.* [56] presented a method related to compensating resolver detected position and also developed a system that can compensate the dynamic errors that vary with a change in rotational speed of the resolver rotor. According to the design, even when the resolver rotor speed becomes high, the resolver position detection accuracy can be enhanced. Based on the use of pseudo linearity of sinusoidal signals around zero crossing, a novel low cost design technique for RDC with basic analog electronics was presented by Mohieddine Benammar *et al.* [57].

Armando Bellini and Stefano Bifaretti [58] explained the necessity of using the filters at lower speeds in order to remove the noise. The paper also proposed a phase locked loop based steady state linear Kalman filter to obtain the filtered speed signal starting from the signals supplied by an electromagnetic resolver. The proposed Kalman filter was based on third order linear time invariant model. Jens Onno Krah *et al.* [59] described a new FPGA based method to convert an analog resolver signals to a digital position signal using delta sigma ADC technology. It is possible to increase the resolution by two bits with second order delta sigma modulator compared to sampling converters. Kamel Bouallaga *et al.* [60] listed the advantages and drawbacks of demodulation methods for resolver signals. They proposed an ATO based algorithm and realized the same by Fusion Field Programmable Gate Array. Jin Woo Ahn *et al.* [61] developed a low cost analog encoder with a proper control method suitable for SRM. The proposed encoder uses a simple structure with an optical analog gradation for high performance of rotor position.

Weera Kaewjinda and Mongkol Konghirun [62] focused on the detection of rotor position of PMSM by the resolver sensor. A resolver algorithm was proposed and implemented in the vector control drive system of PMSM. The algorithm was verified by both simulation and experiment using MATLAB/Simulink and the TMS320F2812 based digital signal processor respectively. Konstantin Veselinov Dimitrov [63] presented a 3-D silicon Hall effect sensor for precision angular position measurement over 360° rotation. The z-axis sensor was introduced to compensate the misalignment of a magnet above the sensor. The angle measurements at this moment were almost performed with the 2-D Hall sensors. Reza Hoseinnezhad *et al.* [64] proposed a new technique to develop the resolver parameters for real time tracking with varying speed and long resting periods. A new recursive and adaptive estimator was designed to track the parameters of characteristic ellipse. The proposed technique is a modified version of recursive weighted least square estimator.

Andrzej Michlski *et al.* [65] created a model of the magnetic circuit for high resolution, multi-pole and two-speed resolvers. They performed an analysis for the influence of manufacturing errors on the resolver accuracy. The created model concludes that high-precision resolver with electrical error well below one minute of arc was possible if an appropriate magnetic material was used and high precision manufacturing was assured. M. Benammar [66] described a novel converter for linearizing the sine and cosine signals of an angle of a resolver sensor. The converter was implemented using ordinary analog electronic components. The theoretical and simulation performances of the proposed converter were also explained. S. K. Kaul *et al.* [67] presented a software based error compensation method for improving the accuracy of low cost resolver based 16 bit encoders. The error profiles of ten encoders were calibrated repeatedly on a high precision rotary table and suggested that error profiles are unique and predominantly systematic in nature for a particular resolver decoder combination. These errors can be corrected by using an appropriate compensation procedure. Non-ideal characteristics of a resolver such as amplitude imbalance, quadrature error, inductive harmonics and excitation signal distortion are also discussed.

Ciro Attainanese and Giuseppe Tomasso [68] proposed the design and implementation of a low cost fully integrated board for RDC based on dedicated analog and digital assembly. This designed board was tested for different resolver speeds. Douglas W. Brown *et al.* [69] proposed a new design for a real time fault detection and accommodation routine for a resolver position sensor. The identified fault detection and accommodation routines were evaluated using Simulink model of an electro mechanical actuator. The proposed design can be applied to already existing Commercial Off-The-Shelf (COTS) resolver sensors without any internal hardware modifications or additional sensors. Lizhi Sun [70] presented a review of various variable reluctance resolver structures and proposed a new variable reluctance resolver structure that is capable of outputting an absolute position signal of the same electrical period as the inverter driven motors. The paper concluded that the position errors mainly come from the odd time harmonics and the null voltages in the signals and proposed several improvement methods including the number of stator poles, changing the stator tooth shape to the salient one and adopting a sinusoidally distributed winding pattern.

Lazhar Ben-Brahim *et al.* [71, 72] developed a new low cost feed forward technique based RDC without look up tables. The proposed method was implemented using low cost analog electronic components and it has the advantage of robustness to amplitude fluctuations of the resolver excitation. Santanu Sarma *et al.* [73] proposed a cost effective software based method for RDC using digital signal processor. The proposed method incorporated software generation of resolver carrier using a digital filter in such a way that there was a substantial savings on costly carrier oscillators and amplitude demodulators. A mathematical model based d-q axis theory and dynamic performance characteristics of brushless resolvers were discussed by D. Arab-Khaburi *et al.* [74]. The impact of rotor eccentricity on the accuracy of position in precise applications was investigated. The proposed model takes the stator currents of brushless resolver into account and the model was used to compute the dynamic and steady state equivalent circuit of resolvers. A complete software implementable scheme for position and speed sensing using a DSP based RDC was presented by S. Sarma *et al.* [75]. The amplitude demodulators and the measurement of position and speed do not cause any time delay and also the dynamics of the proposed system was not affected. The correct functioning and outstanding performance of the proposed RDC was shown both by simulation and experimental results.

The optical encoders do not provide robustness comparable to electrical motors and resolver provides better mechanical robustness but their resolution was not sufficient for good speed control behaviour. So, the capacitive encoders are an attempt to develop to combine good robustness with higher resolution [76]. Analog Devices [77] has proposed a monolithic RDC IC AD2S1210 which completes a 10 bit to 16 bit resolution tracking. A type II servo loop was employed in the proposed AD2S1210 to track the inputs and convert the input sine and cosine information into a digital representation of the input angle and velocity. Lazhar Ben-Brahim *et al.* [78] developed feed forward technique based a new low cost RDC to convert the amplitude of sin and cosine resolver output signals into a measure of the input angle without using look up tables. The proposed design method offered the advantage of robustness to amplitude fluctuations of the resolver excitation signal. Seon Hwan Hwang *et al.* [79–81] proposed a new compensation algorithm to reduce rotor position errors between the resolver output signals caused by amplitude imbalance in vector control drive system of PMSM. The presented method does not require any additional hardware and reduces computation time with simple integral operation according to rotor position.

Zhang Haixial and Yanlan [82] described the working principle, hardware configuration and software design of synchro RDC based on PXI bus. The digital converter of synchro RDC converts analog angle signals into digital signals then connected to computer through PXI. Thus the intelligence of the instrument was realized. Zhuangzhi Han *et al.* [83] proposed tangent algorithm based RDC to digitize the angle information of the two speed resolvers. The proposed algorithm is simpler than traditional tracking algorithm. An analog shaping network for the linearization of resolver output signals and linear determination of rotor shaft angle was proposed by Mohieddine Benammar *et al.* [84] and is based on tangent/cotangent technique. The optimal breakpoint positions of the shaping network were determined experimentally and LabVIEW based setup in order to minimize the non-linearity of the converter output.

V. K. Dhar *et al.* [85] developed an Artificial Neural Network (ANN) based error compensation method to improve the accuracy of low cost resolver based 16-bit encoders for their respective systematic error profiles. The method allows to use the existing resolvers at an accuracy which is within the limits of the encoder resolution. The proposed method was implemented for four encoders by training the ANN with their respective error profiles. Ilpakurty Ravi and K. Nagabhushan Raju [86] discussed about interfacing of a resolver based motor to a servo drive with an incremental encoder interface and developed the hardware to convert resolver interface to incremental encoder interface based on AD2S80 and microcontroller 8051F310. The hardware interface was tested with permanent magnet synchronous motor at speeds up to 1000 rpm. A new technique for angular position and speed sensing of an imperfect resolver angular sensor was presented by Santanu Sarma and A. Venkateswaralu [87]. The proposed method was compared with PLL based RDC. This design provides accurate estimation of the imperfect phase quadrature and magnitudes. The correct functioning and performance of the proposed RDC has explained both by simulation and experimental results.

Mohieddine Benammar *et al.* [88] described an analog converter for the linearization of sine and cosine signals and linear computation of mechanical shaft angle of a resolver. The designed converter was based on a simple two breakpoint shaping network used as linearization scheme. Nicolas Javahiraly *et al.* [89] proposed a new optical fiber angular position sensor connected to an automotive power steering column. The developed sensor was based on the coupling between the guided modes and the radiated modes of the fiber during the light transmission. Multimode step index fiber was used for the design and the sensor allows the measurement of angular position of a car steering wheel over a large range. Sinusoidal amplitude detector based demodulator for resolver converters was presented by Anucha Kaewpoonsuk *et al.* [90]. The designed circuit produces two output signals proportional to sine and cosine envelopes of resolver shaft angle without low pass filter.

A single CMOS type II tracking resolver to digital converter RDC5028 was designed by Aeroflex [91]. This monolithic chip was implemented using precision analog circuitry and digital logic. S. H. Hwang *et al.* [92] proposed a new compensation algorithm for the gain and offset errors of the sinusoidal encoder signals. The effectiveness of the proposed method was verified experimentally. Lazhar Ben-Brahim and Mohieddine Benammar [93] presented a low cost closed loop design method for resolver to analog conversion based on classical phase locked loop. The proposed design was implemented without the use of voltage controlled oscillator, digital to analog converter, counter and look up tables. Zhu Yi *et al.* [94] developed a method to improve the software approach of using the resolver to digital conversion. In the original approach, the samples were taken at positive peak values of excitation signal which increases system complexity. In the proposed method, the sample information was taken at other positions in an excitation period.

Ralph Kennel [95] proposed a scheme for encoderless control of synchronous machines with permanent magnets. The proposed scheme has no limitations with respect to a minimal speed and the drive was able to provide full torque in encoderless operation even at stand still. Cheon Soo Park [96] presented a method and apparatus to minimize the magnetic interference in a variable reluctance resolver. The proposed apparatus comprised a source generation unit for generating a uni-phase source signal to excite a resolver. Joan Bergas *et al.* [97] implemented high accuracy all digital RDC. The basic components of the conventional tracking RDC was implemented in software by using frequency shifting technique and a decoupled synchronous reference frame based phase locked loop. Zhu Ming *et al.* [98] presented a design method for RDC in frequency domain. The proposed design method was based on transforming the complex signal into frequency domain and the components at the carrier frequency are used to calculate the angular position of the resolver.

Jiebin Zhang *et al.* [99] introduced the operating principle, circuit design, algorithm structure, and feasibility analysis of a high precision shaft angle acquisition system used in the solar panel. The system was implemented with absolute round induetosyn as angle sensor, the direct digital synthesizer, RDC and the AVR microcontroller. H. Loge and L. Angerpointner [100] explained the overview of the sources of angular errors and how they will be affect the resolver signals. There are a couple of mechanical, magnetic and electrical reasons that causes perceptible distortions of the resolver signals with results in noise and harmonic ripple on the angular information as well as derived velocity information. A trained artificial neural network algorithm was proposed to replace the demodulation of RDC by Prerna Gaur *et al.* [101]. The proposed resolver algorithm was implemented in the current controlled drive system of PMSM.

Qi Xun Zhou [102] analyzed the working principle and a couple of typical fault of sine-cosine resolver. High reliable sine signal generator for the sine-cosine resolver was designed and the RDC circuit with its mathematical model was also presented. Software based Mallat algorithm was proposed for the fault diagnosis. Ruijie Zhao *et al.* [103] described the use and working principle of resolver and explained the decoding arithmetic of resolve to digital converter. The decoding software arithmetic method was based on angle tracking observer. The proposed method has the smooth ability but also can track the motor rotor position and rotor speed in the same time compared to the inverse trigonometric function method. Anna K. S. Baasch *et al.* [104] presented digital Finite Impulse Response (FIR) filter methods to measure the speed and position of a RDC. The proposed algorithm was implemented in a fixed point digital signal processor based control.

Kazuya Sakai [105] invented a rotational angle sensor that detects the rotational angle with a high degree of accuracy and in which the number of magnetic poles may be flexibly changed. The invented system has rotational angle sensor, a motor, a rotational angle detector and an electric power steering system. Davood Arab Khaburi [106] proposed a modified software based angle tracking observer method for RDC to extract the rotor angle in high speeds as well as in low speeds. The proposed estimated algorithm was based on the sign and absolute values of sine and cosine of the rotor angle. Demodulation of resolver signals using synchronous demodulator is proposed by Idkhajine *et al.* [107, 108]. A fully integrated Field Programmable Gate Array (FPGA) board is used for a synchronous motor drive. One sole ADC is used for performing sampling and ADC. A DSP-based controller for PMSM servo drives using a resolver is presented by Kaewjinda and M. Konghirun [109]. The resolver is excited by a separate signal source at 1 kHz. The resolver outputs and excitation signal are sampled with a sampling frequency of a 10-kHz. The rotor shaft position and speed are computed by using closed loop angle tracking algorithm. As the frequency of the excitation is low, this method is limited to low speeds.

The design of RDC converter without a processor or LUT was reported by A. Kaewpoonsuk *et al.* [110]. This RDC employs the OTA-based inverse-sine function circuit to generate angular output. A steady-state linear Kalman filter-based PLL is proposed by A. Bellini *et al.* [111, 112], to obtain velocity information by reducing noise from the derivative operation. The Kalman filter has the expected angular acceleration of the shaft, which is not always available, as input. Moreover, the Kalman filter has the disadvantage that the gain vector for correcting the predicted state, which plays an important role in the dynamic characteristics of the speed control loop, includes a trial-and error selection procedure, making this technique difficult to implement.

3. Conclusions

In this paper, different design techniques available in the literature using analog, digital and hybrid circuitry for measurement of resolver rotor shaft angle are discussed. From the literature, two basic methods are used for the measurement of angle, namely inverse tangent method and angle tracking observer or Type-II tracking loop method. Inverse tangent method is an open loop method so the design of RDC using this technique is simpler but it gives poor angle tracking performance. Whereas angle tracking observer is a closed loop method, tracks the resolver angle every time and gives good angle performance. The researchers have paid more attention to reduce the complexity in the hardware by implementing software based excitation source to the resolver. It is also proved that the software based RDCs improve the linearity, accuracy, resolution of the angular position.

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