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Proportional Integral Derivative-Reconciling Neuro Fuzzy Controller on Switched Reluctance Motor for Speed Control

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ABSTRACT

Background: The development in power electronics and high-tech control techniques, as well as the advancement of high speed microcontrollers with controlling computation capability, made Switched Reluctance Motor (SRM) drives to work under the various applications. The requirements for variable-speed SRM drives include good dynamic and steady state responses, minimum torque ripple, low speed alternation, and robustness. **Objective:** Due to the important nonlinearity of the electromagnetic property and the coupling relationships in the middle of flux linkage, torque, and rotor position, it is not effortless for an SRM to get acceptable control characteristics. Existing works on Modified PI-Like Fuzzy Logic Controller work shorten the program difficulty of the controller by reducing the amount of fuzzy sets of the Membership Functions (MF) without losing the system performance and stability via the adjustable controller gain but speed control of motor are not achieved. To overcome the issue related to speed control, plan to build a Proportional Integral Derivative with Reconciling Neuro-Fuzzy (PID-RNF) Controller for the Switched Reluctance Motor (SRM). **Results:** Torque- ripple Value percentage is reduced due to the output signal of RNF ΔS_N is the input of the output scaling factor and thereby minimize the vibrations and increases the lifetime of the machine. **Conclusion:** The PID-RNF controller controls the speed of SR motor. The dynamic response of the SRM adapt with the RNF controller during the process and under varying disturbances

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INTRODUCTION

Switched Reluctance Motors (SRM) has a broad variety of applications in industries, mostly due to the particular properties of the motor. High reliability, the high ratio of torque to power, robust contracture, low cost, high effectiveness, high torque and low speed are only a small number of advantages in SRM. The SRM is referred to as an especially relevant pole due to the relevant pole of its stator and rotor structure (Amissa Arifin *et al*., 2012). Relevant pole refers to the arrangement of the element protrude from the oppression into the air gap. The rotor and the stator are completed of steel laminations, and only the stator poles have windings determined around it. The rotor, on the other hand, is free from windings, magnets and brushes. The windings on one of the stator pole are connected in series with the opposite stator to form one phase. It approved in such a way that more than 2 opposite stator poles form one phase.

SRM torque ripple and radial force are the main roots of acoustic noise generation presented in (M. Divandari and M.M. Kabir, 2011). Noise sources in electric machines are normally classify as magnetic, mechanical, electronic and aerodynamic as far as the production of direct airborne noise is concerned. The acoustic noise measured around an SRM is established to be openly correlated to the radial vibration of the stator yoke due to the radial magnetic energy. The sliding mode control (SMC) presented in (Longyong Zhou *et al*., 2012) is not sensitive to the changes of the system parameters and the external disturbances. Moreover, SMC realize fast dynamic response and be implemented on digital computers easily.

PMSM MC-fed drives are the so-called Field-Oriented Control (FOC), which requires the permanent magnet flux position to attain high active performance. MC-based hybrid sensor less Field- Oriented Control

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(FOC) is presented in (Antoni Arias *et al*., 2013) with a smooth transition from a non-model-based signal injection method at low speeds to a model-based flux estimator at higher speeds.

An elementary equivalent circuit for the SRM is already derived in (S. R. Mousavi-Aghdam *et al*., 2012) by neglecting the magnetic hysteresis loss, the mutual inductance among the phases and eddy current loss. The variable structure control system (VSCS) is a control law which intentionally altered during the control process depends on the nature of SRM drive. DTC for ac drives is an approach completely based on stator voltage control. The consecutive voltage vectors applied to the motor are openly selected on the basis of torque and flux errors as presented in (M. Jafarboland and H Abootorabi Zarchi 2012). The switching gain in (Xiaojie SUN *et al*., 2013)is great enough to assure a good performance when the model uncertainties or outside disturbances are unknown. The corresponding uncertainty compensator is predictable to get better integral sliding mode control presentation via utilizing the sliding manifold affected by the uncertainties.

Because of the mentioned reasons, SRM has undergone quick development in mixture vehicles, wheelchairs, aircrafts, starter/generator systems, washing machines and other automotive applications. The main difficulty of the motor is that it produces high torque ripples. Torque control is a complex task since the switched reluctance motor is intentionally operated in profound magnetic saturation to augment the output power density. Combined contactless power supply (CPS) and electromagnetic guiding system (MGS) is division of an inductive energy transmission consists of an omega shape iron yoke with enduring magnets and coils on its lateral arms (R. Appunn *et al*., 2013). The contactless power transmission result in a communication of the two principles.

Combine these optimization ways together with harmony optimization of SRM as shown in (Jie Li *et al*., 2010). Control optimization is about the control mode, turn-on Physical design is mostly aiming at the back iron thickness and the air gap period of the motor turn-off angle which affect the power factor powerfully. SRM with modified pole shapes such as stator pole taper, stator pole face with non-uniform air gap and pole shoe friendly to rotor pole. A thorough sensitivity analysis of the consequence of dissimilar geometrical parameters that alter the pole face shapes on the performance of SRM (Dr. M. Balaji *et al*., 2013). The control strategies used are PI Control, Hysteresis Control and voltage control are obtained from simulation has been established virtually. The control signal and circuit design for process of a Switched Reluctance Motor (SRM) drive has been described in (Vikas S. Wadnerkar *et al*., 2008).

The precise knowledge of the rotor position is necessary for high-quality performance of the switched reluctance motor drive. The entry of SRM in the sensitive applications in industries has proved the obligation for extremely reliable and fault tolerant rotor position sensing methods. The need for the rotor angle information in SRM has been conventionally pleased by the use of some form of rotor position sensor (R. A. Gupta *et al*., 2010). Rotor position sensing is an essential part of SRM control since of the environment of reluctance torque production. In truth, excitations of the SRM phases require to be appropriately coordinated with the rotor position for effectual control of speed, torque and torque pulsation.

The rule bases are created based on the knowledge of the SRM’s active behavior and sensible experience as shown in (Shun-Chung Wang and Yi-Hwa Liu, 2011). Modified PI-Like Fuzzy Logic Controller work shorten the program difficulty of the controller by reducing the amount of fuzzy sets of the Membership Functions (MF) without losing the system performance and strength via the adjustable controller gain but speed control of motor are not achieved. Fuzzy logic based simulation for a 6/4 SRM for rotor position sense using fuzzy logic to enhance the performance of an SRM (Vikas S. Wadnerkar *et al*., 2010). It’s not implemented in fuzzy controller to assist further research.

SRM teeth widths are altered and the collision of that on the torque ripples is monitored. Next, the core back width is widened and the get in touch with of that on the torque ripples is studied. As a final point, the transmission period of each phase is chosen using the mathematical procedure of overlapping region in the reluctance type motors (Dr. Eyhab and El-Kharashi 2010). The mathematical formula for calculating the overlap region is calculated and used to check the wide core back SRM animatedly; the results exemplify very low torque ripples.

Adaptive Neuro Fuzzy Inference System (ANFIS) it overcomes the disadvantages of sensor scheme as presented in (S.Kanagavalli and A.Rajendran, 2013) and also it does not require any mathematical models and large lookup tables to predict the position angle. Then position estimation based on fuzzy and ANFIS are compared, where the rotor position or angle is estimated by using the relationship between flux linkage and phase current based on fuzzy rule base. An optimization using fuzzy strategy is presented successfully after sensitivity analysis in (S. R. Mousavi-Aghdam *et al*., 2012). The switched reluctance machine is well suited for electric and hybrid electric vehicles, due to the easy and rugged construction, low cost, and aptitude to function over a wide speed range at constant power for e-series hybrid electric vehicles is investigated.

Linear switched reluctance motor (LSRM) as presented in (J. Garcia Amoros and P. Andrada, 2010) is based on an analytical formulation of the standard propulsion force determined using the non-linear energy conversion loop, in which the unaligned magnetization curve is unspecified to be a straight line and the aligned magnetization curve is represented by two straight lines. The design is based on a logical formulation of the standard propulsion force strong-minded using the non-linear energy conversion loop. Doubly-Fed Induction Machine (DFIM) drives are designed in (Amir Farrokh Payam, 2008) based on the adaptive input-output feedback linearization control technique, using the fifth order replica of induction machine in permanent stator with state variables.

In this work, the goal of PID-RNF controller is to achieve SRM speed control according to the need by identity tuning of Proportional Integral Derivative controller. For this purpose, the active model is obtained using the position of the rotor, flux current and torque current values respectively by finite component investigation. The proposed PID-RNF controller is divided in two phases. The first phase employs Reconciling Neuro-Fuzzy Controller to produce model reference variations, based on speed error and its change. The second phase employs Proportional Integral Derivative that optimizes the torque, based on rotor position.

Using model performance, PID-RNF controller is compared with the performances of FL controllers with respect to speed control in terms of time. PID-RNF controller shows a remarkably improved performance over its conventional system on a 8/6 pole SRM drive based on motor speed, torque ripple factor, load disturbance factor. PID-RNF controller used to practically verify the features of the control strategy.

The rest of the paper is organized as follows. Section 1 gives the brief explanation of Switched Reluctance Motor and describes about the different existing work with their confines. Section 2 develops a proportional integral derivative-reconciling neuro fuzzy controller to achieve the stability via the adjustable controller. Section 3 presents the effective results on the PID-RNF Controller for the Switched Reluctance Motors to achieve the feasible solution. Section 4 summarizes the performance of a four-phase 8/6-pole SRM with the table and graph values.

2.0. Proportional Integral Derivative-Reconciling Neuro Fuzzy Controller:

PID-RNF controller is obtained using the position of flux current rotor and torque current rotor values obtained through finite constituent analysis. The PID-RNF controller system under study is shown in Fig. 2.1. It consists of the SRM provided with its prescribed power supply. The data of the motor is given in the appendix. The drive is tested under the following condition in such a manner that initially the motor is started using the full load torque until the motor reaches the speed 2500 rotation per minute (rpm). Then, the motor is subjected to a speed reference interruption where the reference speed is unexpectedly increased to 3250 rpm, followed by another sudden increase with the reference speed interruption to 3000 rpm.

The block diagram as shown in fig 2.1 is divided into two phases. The initial phase employs Reconciling Neuro-Fuzzy Controller based on speed error and its transition state.

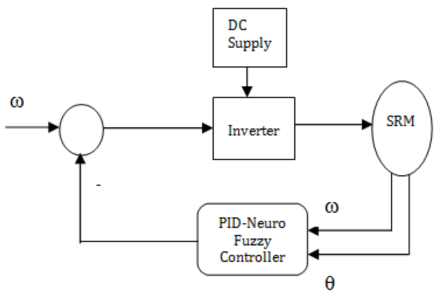

Fig. 2.1: Block Diagram of SRM speed control using RNF.

The second phase employs Proportional Integral Derivative for optimizing the torque, based on rotor position. The knowledge of rotor location is of essential to control the speed of a SRM drive, since with the rotor location the decision regarding the phase to be supplied, positive or negative torque is taken under consideration.

Moreover, another feature in PID-RNF controller affects torque control. In order to estimate the phase current and phase torque in the active PID-RNF controller when the input voltage and rotor position are known, it verifies the current lookup table and torque lookup table. The current look up table and the torque look up table are designed using the location information of the flux current and the torque current respectively.

PID-RNF uses the 8/6-pole SRM for input and it measures the voltage point. The connection port is set up as 1 with DC supply. It also uses the controlled current.

2.1. Reconciling Neuro-Fuzzy Controller Preliminaries:

The first phase involved in the design of PID-RNF controller is combination of plant PID information and fuzzy logic control that plays very important role in the advanced control techniques. Moreover, it adheres with lots of advantages such as flexible, accurate and robust PID-RNF controller. The actual speed ‘u’ is compared with the reference speed u_{ref} to yield the speed error s (t). The incremental change of speed error Δs (t) are expressed as follows,

$$\Delta s(t) = s(t)s(t-1) \tag{1}$$

The PID-RNF controller has two input scaling factors of gains Gain $_s$ and Gain $_{\Delta s}$ and also one output scaling factor of gain $Gain_{\Delta u}$. The output signal of PID-RNF is given as the input scaling factors, which is written as follows,

$$\Delta S_N(t) = \Delta S_N(t). Gain_{\Delta s} \tag{2}$$
$$S_N(t) = S(t). Gain_s \tag{3}$$

The output signal for the input scaling factors S_N and ΔS_N are considered to be the inputs of the Reconciling Neuro Fuzzy (RNF) controller. The output signal of RNF is the input of the output scaling factor. The plant structure of Proportional Integral Derivative has two inputs s (t) and Δs (t), output signal β is used to superior tune the output scaling factor. The output indication of PID output scaling factor are represented by the following equation,

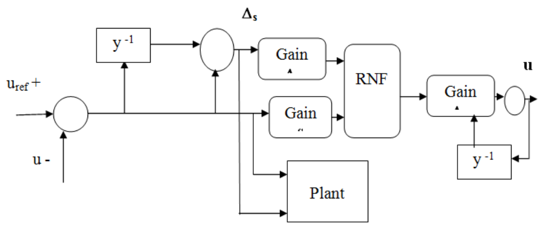

Fig. 2.2: Block Diagram of Reconciling Neuro-Fuzzy Controller.

$$\Delta u(t) = \Delta u_N(t). \beta. Gain_{\Delta u} \tag{4}$$

The simply output signal of RNF controller u (t) written as follows,

$$u(t) = \Delta u(t) + u(t-1) \tag{5}$$

In practice, the proposed Reconciling Neuro-Fuzzy controller presents a logic controller with tuning using the self scaling factors as shown in Fig 2.2. During the initial stage, the neuro fuzzy logic control rules are described to identity tune the output scaling factor of the controller. Reconciling Neuro-Fuzzy Controller makes sure an excellent reference pathway of the switched reluctance motor drives. The RNF controller is found to improve the speed directive type of drives over both starting and reference speed interruption periods. The response is found to be superior to that of the conventional PID controller.

2.2. PID Membership Function:

For the PID-RNF, the membership functions were defined off-line, and the values of the variables are selected according to the behaviour of the variables observed during simulations. The control rules of the RNF controller are symbolized by a set of chosen neuro-fuzzy rules. The designed neuro-fuzzy rules used in this work are given in Fig 2.3. The neuro-fuzzy sets have been defined as, NB as Negative Big, NA as Negative Average, NM as Negative Minute, ZR as zero, PM as Positive Minute, PA as positive Average and PB as Positive Big respectively.

On the other hand, input information were selected as equal to the number of input signals and the output information as equal to the number of output signals.

The number of information is generally taken as the mean of the input and output nodes. The inputs are consisted of the speed error s (t), and the change in speed error Δs (t). The output is the signal β, which has certain value between -1 and +1.

	S_N							
ΔS_N		NB	NA	NM	ZR	PM	PA	PB
	NB	PB	PB	PA	PA	PM	PM	ZR
	NA	PB	PA	PA	PM	PM	ZR	NM
	NM	PA	PA	PM	PM	ZR	NM	NM
	ZR	PA	PM	PM	ZR	NM	NM	NA
	PM	PM	PM	ZR	NM	NM	NA	NA
	PA	PM	ZR	NM	NM	NA	NA	NB
	PB	ZR	NM	NM	NA	NA	NB	NB

Fig. 2.3: Description of RNF rules.

2.3. Pseudo code Flow of PID-RNF Controller:

Begin
Input: Reference Speed (N_{ref}), rpm
Output: SRM speed control with tuning by self scaling factors
Step 2: If (rpm=2500 rpm)
Step 3: Normal speed of information
Step 4: Else if (rpm>2500)
Step 5: Read the speed error
Step 6: Apply Reconciling Neuro-Fuzzy Controller
Step 7: Select the rule to overcome the error
Step 8: End if
Step 9: End if
Step 10: Calculate the gain s (t)
$\Delta s(t) = s(t)s(t-1)$

Step 9:
End

The PID-RNF Controller algorithm is the active model of SRM and solves simultaneously with the aid of the RNF rules as shown in Fig 2.3.The membership rating values corresponding to PID are obtained from a singleton membership function. Once the Reconciling Neuro fuzzy inference results are attained from the inference engine, the actual control output are obtained from the process to get the SRM plant output. In research, the inferred Reconciling Neuro fuzzy control action is converted to a plant effective value by controlling the speed.

3.0. Evaluation Result of Proportional Integral Derivative-Reconciling Neuro Fuzzy Controller:

The proposed PID-RNF Controller is constructed by a PC through a friendly user interface of Matlab real-time coding is generated. The following are the high system integration, speed control algorithms easily programmed through the friendly IDE, and the feasible compiling codes are conveniently written to the DSP to shorten the development and debugging time. The time estimator using existing Modified PI-Like Fuzzy Logic Controller is c=0.0749, whereas using PID-RNF Controller the time estimator c = 0.0107 % which is decreased to improve the motor speed/sec.

Existing PI-LFL Controller rule based method are plotted in ‘x’ and ‘y’ axis. The degree value of PI-LFL Controller ranges from the -1000 to 1000 that is plotted with MATLAB strings. SRM Motor Drives system of PI-LFL Controller is shown below in Fig 3.2

PI-LFL Controller offer advantages of higher power density, higher efficiency, and wider speed range. The corresponding control and operation of the motor drive contain two operation modes, namely, four-phase (red) and two-phase (blue) operation modes are proposed for the 8/6-pole SRM motor drive.

Performance metric for evaluation of proposed PID-RNF controller technique is measured in terms of motor speed, torque ripple factor, current consumption, accuracy rate, and load disturbance factor.

Motor speed tracking is the amount of time it takes to perform one revolution whereas the time measured in terms of seconds (sec) with the torque ripple factor defined as the effect produced using SRM motor designs, referring to a periodic increase as the output shaft rotates. It is measured as the difference in maximum and minimum torque over one absolute revolution, normally expressed as a percentage.

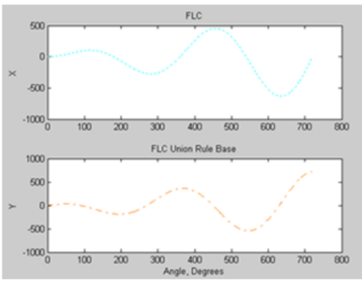

Fig 3.1: PI-LFL Controller Union Base Rule Angle and Degree.

Load Disturbance is often encountered in SRM 8/6 pole as the process of identifying the procedure and detect the load changes. The load changes are detected in existing PI-LFL Controller and proposed PID-RNF controller find the quality model under load disturbance.

The load disturbance of existing PI-LFL Controller and proposed PID-RNF Controller is show in fig 3.3 (a) and (b) respectively it is evident as the time increases the load factor decreases from 0.1220 to 0.0275 in proposed PID-RNF Controller system.

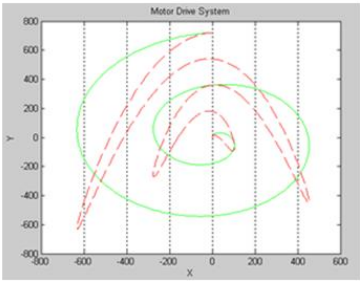

Fig. 3.2: Motor Drive System of PI-LFL Controller.

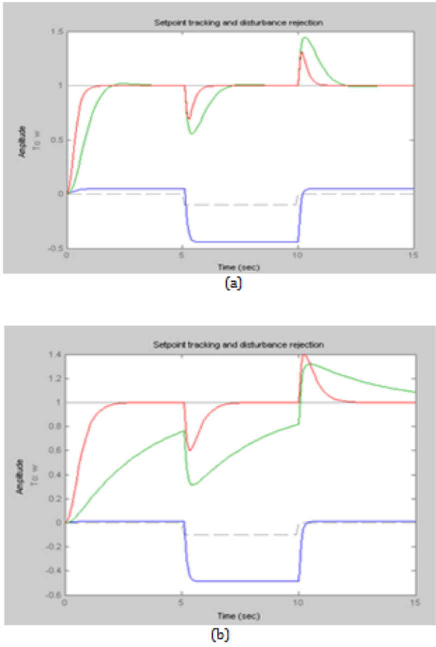

Fig. 3.3: Load disturbance factor using (a) Existing PI-LFL Controller (b) PID-RNF Controller.

The load disturbance is reduced due to the Reconciling Neuro-Fuzzy Controller that makes sure an excellent reference pathway for reducing load disturbance in 8/6 pole. The RNF controller is found to improve the speed directive type of drives over both starting and reference speed interruption periods.

4.0. Performance of PID-RNF Controller over Modified PI-LFL Controller:

The performance of the proposed Proportional Integral Derivative with Reconciling Neuro-Fuzzy (PID-RNF) Controller is measured against the Modified PI-Like Fuzzy Logic Controller and plotted in bar chart. The table given below and graph describes the performance of the system with SRM 8/6 pole. From point it is aimed to design PID-RNF control speed of 8/6 pole SRM and increase control performance of the motor. Flux and torque current rotor location values of a SRM 8/6 pole are obtained, where the dynamic model of the motor is derived with the aid of these values.

Table 4.1: Motor Speed Tracking.

Time (sec)	Motor Speed Tracking (rpm)	
	Existing PI-LFL Controller	PID-RNF Controller
0.5	0.0101	0.1010
1	0.1000	3.1000
1.5	1.1000	4.1000
2	2.1000	5.100
2.5	3.1000	6.100

PID-RNF gives a better performance for the SRM speed control under no-load and load conditions. The motor speed tracking is measured based on the speed it travels as shown in table 4.1. It shows the speed response of the proposed PID-RNF and also that obtained with the existing PI-LFL Controller. As the time

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increases in terms of sec, motor speed tracking is also increased that is measured in terms of rotation per minute (rpm). The table and graph shows the effective result on the SRM 8/6 pole device. PID-RNF Controller is approximately 20 – 25 % improved result when compared with the Existing PI-LFL Controller because membership functions were defined, and the values of the variables are selected according to the behavior of the variables. The behavior of the variables accordingly improves the speed when compared with the existing PI-LFL Controller.

Table 4.2: Torque- Ripple Value.

Speed	Torque- ripple (N-m)	
	Existing PI-LFL Controller	PID-RNF Controller
2000	0.0032	0.001143
2500	0.00227	0.001143
3000	0.0018	0.001173
3500	0.0018	0.001128
4000	0.0013	0.000850

The torque ripple one of the significant parameter to be measured based on the speed being applied when designing a machine. The value of the torque ripple value decreased with the increase in the speed. The above table 4.2 compares the existing PI-LFL Controller with the PID-RNF Controller. Fig. 4.2 describes the torque ripple value on the SRM 8/6 pole device. Torque- ripple Value percentage is 30- 40 % reduced due to the output signal of RNF ΔS_N is the input of the output scaling factor and thereby minimize the vibrations and increases the lifetime of the machine.

The plant structure of probability Integral Derivative has s (t) and Δs (t), output signal β to improve the superior torque ripple tune on the output scaling factor with the speed varying from 2000 rpm to 4000 rpm

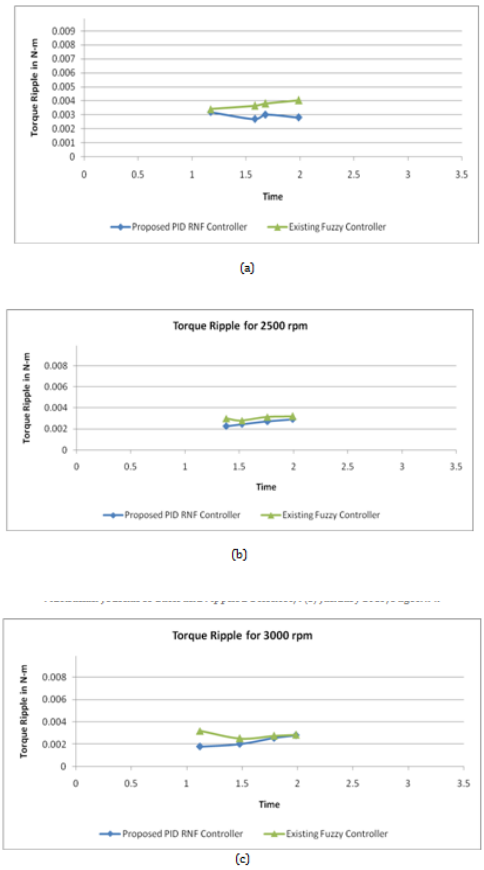

Fig. 4.2: Measure of Torque-ripple as a function of speed on SRM 8/6 pole device with PI-LFL Controller and PID-RNF Controller a)for 2000rpm b)for 2500rpm c)for 3000rpm.

Table 4.3: Load disturbance.

Speed Change	Load Disturbance	
	Proposed PID – RNF Controller	Existing Fuzzy Controller
2000 - 4000	0.9901	9.9010

Table 4.3 describes the different load disturbance value for the speed ranging from 2000 to 4000 rpm. The load disturbance is 70- 75% improved due to the output signal of RNF ΔS_N is the input of the output scaling factor and able to deal with the changes in load more efficiently. The plant structure of probability Integral Derivative has s (t) and Δs (t), output signal β to improve the superior torque ripple tune on the output scaling factor with the speed ranging from 2000 to 4000 rpm.

As the final point, 8/6 pole SRM has been developed for the switched reluctance motor speed. The response is found to be superior to that corresponding to the conventional PID controller. The better system performance by making the steady state errors tend to zero in PID-RNF Controller. The lower load demand has a gain factor by estimating and compensating the effect of uncertainty.

5.0. Conclusion:

Proportional Integral Derivative with Reconciling Neuro-Fuzzy (PID-RNF) Controller for the 8/6-pole SRM is used for speed control of SR motors. The dynamic response of the SRM is to adapt with the RNF controller during the process and under different disturbances. PID-RNF enhances the speed regulation of drives over both starting and reference speed disturbance periods. To describe with the minimal fuzzy logical rules and torque time constant‘s’, self tune develops the output scaling factor of the controller. The response is established to be greater to that corresponding conventional PI controller. The combination of SRM with lesser fuzzy logic control plays very significant position with many advantages such as flexible, precise and vigorous controller. Experimental outcome produces the effective speed of 8/6-pole SRM, improved torque ripple factor, and reduces the load disturbance in devised PID-RNF controller.

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