Robust Modified Structured NFC Integrating with GA for Linearized Induction Motor Drive

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***Abstract*—This paper presents a development of a simplified neuro-fuzzy control (NFC) based on genetic algorithm (GA) for optimal performance of induction motor (IM) drive using feedback linearization (FBL) approach. An intuitive linearization technique based IM is modeled and simulated in the stationary *d-q* reference frame. The proposed simplified NFC with GA (SNFC-GA) incorporated with FBL reduces the torque ripple and improves the speed response of the IM drive. This novel technique also has the benefit of reduced computational burden by improving computational efficiency over conventional NFC and thus, suitable for real-time industrial applications. Moreover, the optimal parameters of the modified NFC are searched by GA in order to ensure the global convergence of tracking error. The effectiveness of the proposed method using linearized IM drive is investigated in simulation as well as in experiment, and it is evident that the system provides optimal dynamic performance and is robust in terms of parameter variations and external load.**

Keywords-feedback linearization; induction motor; simplified NFC; genetic algorithm

I. INTRODUCTION

Over the years, induction motors (IMs) control has been a focus area of investigation in the industry as well as in academia. However, the control technique for designing high-performance IM drive is quite complex due to its nonlinear dynamics and parametric uncertainties [1], [2]. The feedback linearization (FBL) controlled IM drive with the conventional PI-controller [3]-[5], [7] has the demerits of ripple in steady-state, load perturbation, and parameter variations due to which the decoupling of flux and torque and dynamic response become poor. To overcome this, sliding-mode control (SMC) incorporated with the linearized IM drive has been proposed effectively in [6] which show robust performance with system uncertainties. But, the SMC has major drawback of introducing often chattering effect in the steady-state control signals. These issues can be overcome by implementing intelligent control algorithm [11], [13] as the controllers are based on human knowledge and experience and thus while designing, these controllers are robust and independent of accurate system model dynamics.

This paper broadly focuses on the adaptive neuro-fuzzy control (NFC) as both fuzzy logic control (FLC) and artificial neural network (ANN) controllers have some uncertainties. The FLC used for adjustable speed drive requires membership functions (MFs) of asymmetric type, i.e. adjusted manually by trial and error if the optimal system performance is needed [8], [9]. On the other side, it is very tough to generate training data for all operating modes of IM drive for ANN [10]. Thus to overcome these demerits of both FLC and ANN, a combined approach known as NFC have been implemented here and by others for IM drive [14]. However, some industries have been still reluctant to acknowledge these controllers for the commercial drive as it has higher computational burden due to a large number of MFs, rules, and weights, especially on auto-tuning condition [12]. The high computational burden leads to high sampling rate which is not acceptable in many industries as it is not suitable for real-time applications due to more torque ripple. Moreover, a quick processor may be required for this high computational control algorithms, which may be costly.

Apart from being resistant to motor parameter variations, system uncertainties, and perturbation of external load, the proposed simplified single-input based NFC reduces the computational burden by lessening the rules and MFs when contrasted with the conventional two-input NFC [15], [16], [19]. However, the back-propagation (BP) algorithm used in NFC for tuning usually cannot ensure the optimal solution. In real-time implementations, the BP algorithm may get trapped in local minimum solution, which leads to an impact on the performance of the drive system indirectly [17]. Further, the performance of the NFC depends largely on the learning rate of ANN, and an unoptimized learning rate makes the network to converge or diverge slowly. Thus, an effective optimization technique GA is adopted with the NFC in order to search the optimized parameters of NFC and to guarantee the global convergence of tracking error. In fact, GAs have been successfully proposed for controller design in various industrial adjustable drives, robotics, etc. where more priority is given to the performance of overall system [18].

The unoptimized learning rate of ANN and the computational burden imposed by the conventional NFC motivate us to develop a new hybrid intelligent controller. This paper employs an innovative controller for an intuitive decoupling FBL controlled IM drive which is different from in [5]-[7] and is based on a suitable adaptive simplified NFC with GA technique. However, the implementation of GA with the modified NFC makes the system effective, robust, and chattering-free. It is evident from the results that the proposed SNFC-GA delivers dynamic characteristics of high-performance industrial drives which are robust on system uncertainties, parameter variations, and external load perturbation. The proposed adaptive SNFC-GA-based

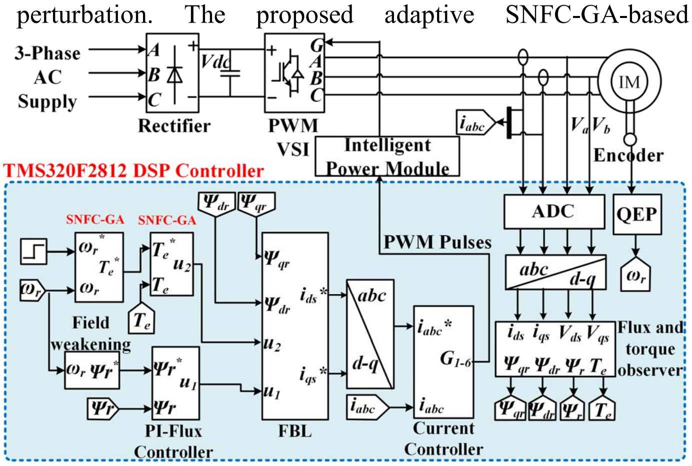

Fig. 1. Proposed modified NFC-GA-based linearized drive.

II. Design of Feedback Linearization Controller

Feedback linearization control is an approach where the linear control method can be implemented efficiently with nonlinear system dynamics. The theoretical approach and design methodology of an intuitive feedback linearization are given in [7], [19].

III. Design of Adaptive SNFC-GA

The combined advantages of adaptive simplified NFC and efficient optimization technique GA are proposed here to get rid of the uncertainties which arise in feedback linearized drive control. The main priority given in this adaptive NFC-GA is to propose a GA-based optimization technique that searches optimal parameters of the simplified NFC under system and parameters uncertainties, external disturbance. However, unoptimized and uncertain FLC and the computational burden imposed by conventional NFC lead to the design of simplified NFC.

A. Proposed Single-input modified version NFC

The proposed simplified NFC design integrates FLC with a four-level ANN organization, unlike conventional NFC as described in Fig. 2. The single input speed error due to the difference of desired speed ω_r* and actual speed ω_r of the NFC is as follows.

$$\%e_s(t) = \frac{\omega_r^* - \omega_r}{\omega_r^*} \times 100 \tag{16}$$

Layer 1: The output of this fuzzification layer having adaptive nodes of three-speed error membership functions (MFs) as negative (N), zero (Z), and positive (P) speed errors are given by

$$O_1^1 = \mu_{M1}(e(t)) = \begin{cases} 1, & x_i^1 \le b_1 \\ \dfrac{x_i^1 - a_1}{b_1 - a_1}, & b_1 < x_i^1 < a_1 \\ 0, & x_i^1 \ge a_1 \end{cases} \tag{17}$$

$$O_2^1 = \mu_{M2}(e(t)) = \begin{cases} 0, & \left|x_i^1\right| \ge \dfrac{b}{2} \\ 1 - \dfrac{2\left|x_i^1 - a\right|}{b}, & \left|x_i^1 - a\right| \le \dfrac{b}{2} \end{cases} \tag{18}$$

feedback linearized IM drive is illustrated in Fig. 1.

$$O_3^1 = \mu_{M3}(e(t)) = \begin{cases} 0, & x_i^1 \le a_2 \\ \dfrac{x_i^1 - a_2}{b_2 - a_2}, & a_2 < x_i^1 < b_2 \\ 1, & x_i^1 \ge b_2 \end{cases} \tag{19}$$

where $\mu_{M1}(e_s(t)), \mu_{M2}(e_s(t)), \mu_{M3}(e_s(t))$ are chosen to be symmetrical (a = 0) linear MFs as in Fig. 3 rather than any exponential function in order to lessen the computational weight and making it more efficient. Here x and O correspond to input and output, and their superscript and subscript denote layer and node number, respectively.

Layer 2: The "AND" logic operator is not used in this layer for the calculation of the weight of rules w_i since only one input is present here unlike conventional two-input NFC. The normalized $\overline{w_i}$ can be written as

$$O_i^2 = \overline{w_i} = \frac{w_i}{\sum_i w_i} \qquad i = 1, 2, 3 \tag{20}$$

Layer 3: The consequent value v_i is calculated in this layer as node equation, which output is specified as

$$O_i^3 = \overline{w_i} v_i \qquad i = 1, 2, 3 \tag{21}$$

Layer 4: This is the defuzzification layer, where the NFC output is determined by center-of-gravity method and is specified as

$$O_i^4 = \frac{\sum_i w_i v_i}{\sum_i w_i} = \sum_i \overline{w_i} v_i \qquad i = 1, 2, 3 \tag{22}$$

The MFs of both the conventional NFC and proposed simplified NFC are kept identical as shown in Fig. 3 in order to make a fair comparison.

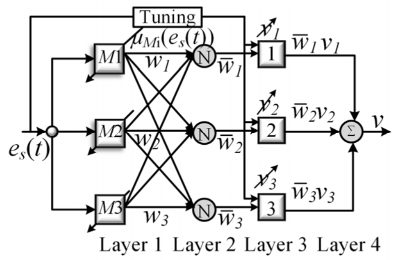

Fig. 2. Proposed modified NFC architecture.

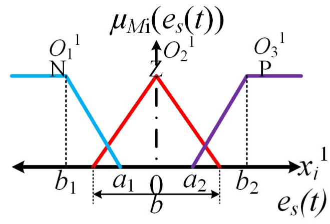

Fig. 3. Conventional NFC architecture

B. GA-based simplified NFC

Some parameters of the SNFC are still unoptimized due to the ANN as it tries to find out the optimal parameters of the FLC and during the process, it may confine at local minima instead of global minima. This leads to an impact on the performance of the drive system indirectly. So, to confront this issue, a powerful optimization method GA is integrated with the proposed SNFC to optimize learning rate of ANN and coefficient of momentum [17]. The modeling algorithm of SNFC-GA is demonstrated in Fig. 4. Since GA controls the training step and picks up the optimized parameters at every iteration, it is not required to rectify the NFC model. Fig. 5 depicts the structure of proposed NFC-GA interfacing with FBL controlled IM drive.

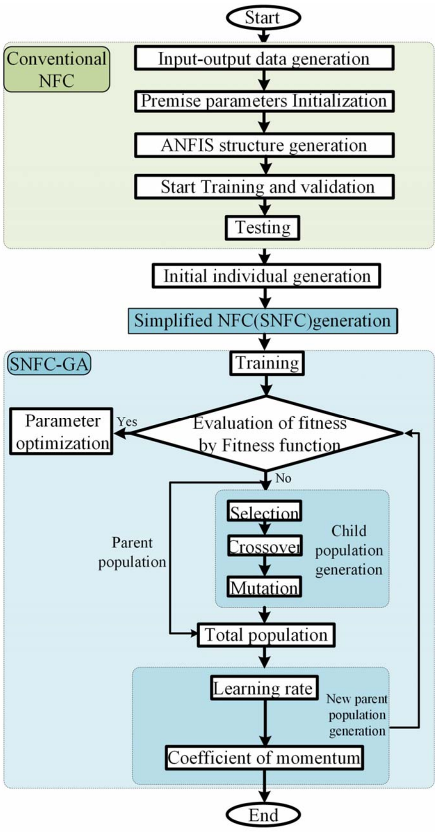

Fig. 4. Flowchart for modeling steps of applied methods using GA.

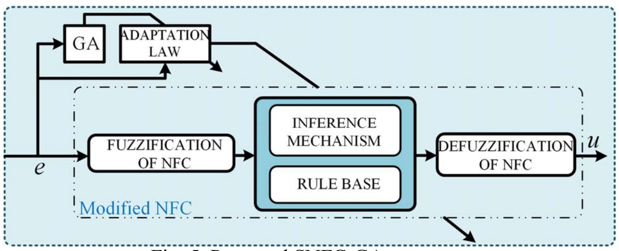

Fig. 5. Proposed SNFC-GA structure.

Instead of setting the desired controller output 'v' as a target, an error signal 'e' which considers the execution of the controller and evaluates the current state of framework is used to deal with the control action into changing in right directions and in addition deliver the desired response [15]. A tuning method based on backpropagation algorithm is used here, which task is to update the MFs parameters and weight so that the error signal is minimized which is defined below as a fitness function.

$$E = \frac{1}{2}(\omega_r^* - \omega_r)^2 = \frac{1}{2}e^2 \tag{23}$$

The parameters of the NFC are updated as follows:

$$u_i(k+1) = u_i(k) - \eta_{ui}\frac{\partial}{\partial u_i}E(k) \tag{24}$$

$$a_i(k+1) = a_i(k) - \eta_{ai}\frac{\partial}{\partial a_i}E(k) \tag{25}$$

$$b_i(k+1) = b_i(k) - \eta_{bi}\frac{\partial}{\partial b_i}E(k) \tag{26}$$

$$w_i(k+1) = w_i(k) - \eta_{wi}\frac{\partial}{\partial w_i}E(k) \tag{27}$$

where k is the sampling instant. a_i, b_i, w_i are the i^{th} node values of a, b, w_i and η_{ai}, η_{bi}, η_{wi} are their learning rates.

The mean square error (MSE) of the SNFC-GA is found to be the least value 0.00158 as shown in Fig. 6. The MSE was shown based on 30 iterations but, prior to five iterations, the controllers are settled down to the minimum error of 0.00187, 0.00175, and 0.00158 for conventional NFC, SNFC, and SNFC-GA, respectively. By checking different values of the parameters, i.e., mutation rate, learning rate, and coefficient of momentum, the GA makes the structure best with faster convergence. The optimized parameters using SNFC-GA are illustrated in Appendix B.

Similarly, the GA operation is also adopted to optimize the NFC parameters for the motor torque dynamics.

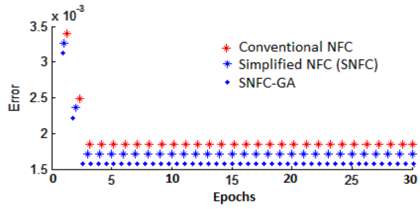

Fig. 6. Comparison of MSE for different controllers.

IV. RESULTS AND ANALYSIS

The performance of the proposed simple modified NFC-GA via FBL controlled IM drive is examined by simulation as well as by experiment. The responses under different working modes are analyzed and compared, and the details are illustrated in Fig. 9. The parameters of IM drive system are given in Appendix A.

A. Simulation Results

Case 1: The FBL modeled IM drive without load at 800 rpm using various controllers is performed under MATLAB simulation, and the responses are shown in Fig. 7. The less distorted stator current improves the starting torque response of the proposed SNFC-GA-based drive by significantly reduced ripple than that of conventional NFC and SNFC based drive. Also, it is evident from the results that the low computational proposed SNFC-based drive has lesser ripple compared to the conventional NFC. On the other hand, SNFC-GA shows superior performance over both conventional NFC and SNFC based drive, which details are demonstrated in Fig. 9.

Case 2: The response of the external load perturbation by increasing the step load to 50% (10 Nm) from 1.5 s to 2 s is illustrated in Fig. 8. It reveals that the speed response of the proposed simplified NFC-GA has very good load disturbance rejection in terms of undershoot and overshoot. The torque ripples with the proposed SNFC-GA are extensively reduced over conventional NFC. In fact, the oscillation in speed is almost disappeared by using the proposed SNFC-GA-based drive compared to the SNFC-based drive, which still has a tiny oscillation as in Fig. 8 (c) (i).

Since sufficient evidences are provided in extensive simulation results, the simplified NFC results are not considered further in Fig. 10 and 11. Fig. 10 reveals that the rotor flux being steady throughout every operating mode regardless of the speed and the proposed low computational NFC with GA establishes perfect decoupling without diminishing the system behavior.

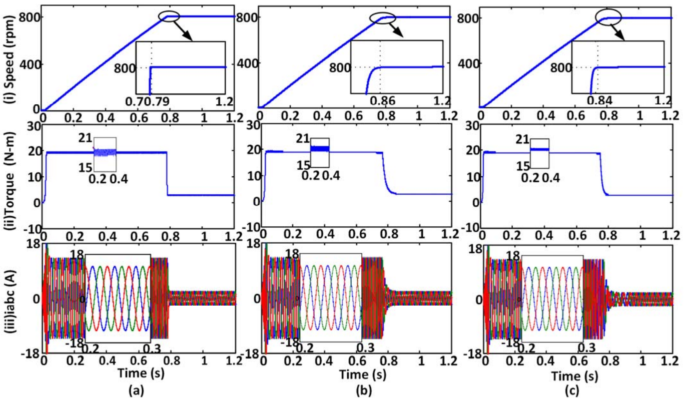

Fig. 7. Responses of FBL modeled IM drive during starting using (a) conventional NFC, (b) proposed SNFC, and (c) proposed SNFC-GA.

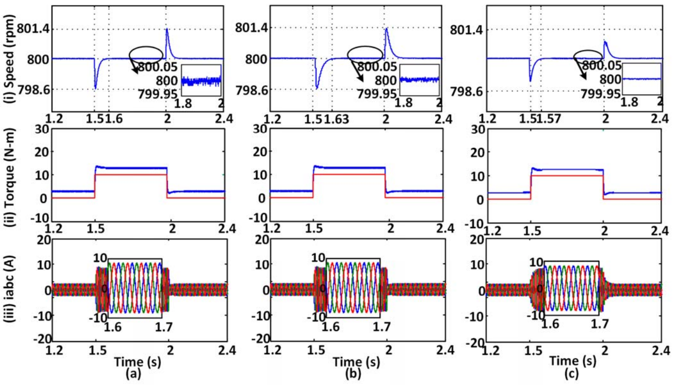

Fig. 8. Responses of load perturbation by step increase of load to 50% using (a) conventional NFC, (b) proposed SNFC, and (c) proposed SNFC-GA.

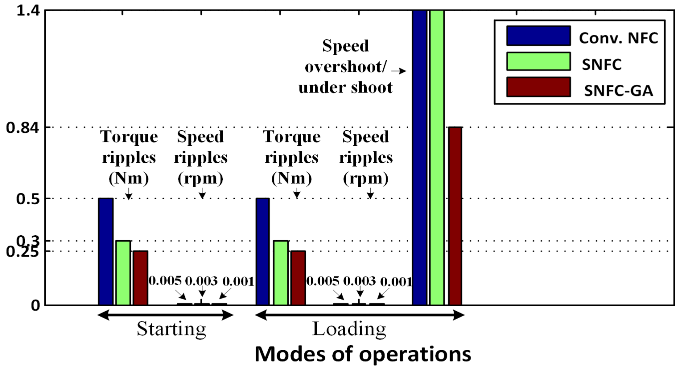

Fig. 9. Comparisons of FBL IM drive using different controllers.

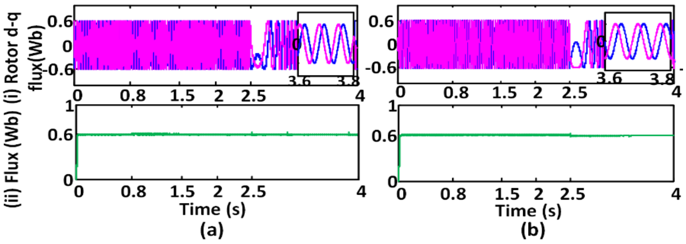

Fig. 10. Flux responses of FBL controlled IM drive using (a) conventional NFC and (b) proposed SNFC-GA.

The robustness of the proposed SNFC-GA-based feedback linearization controller in face of the motor parameter detuning is examined with the doubled rotor inertia and resistance as shown in Fig. 11. The settling time response is almost doubled as the rotor inertia is doubled. The responses demonstrate the robust stability of proposed SNFC-GA-based linearized drive.

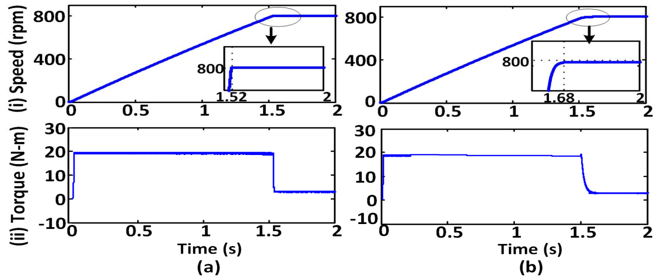

Fig. 11. Startup responses of FBL IM drive with twice of rotor resistance and inertia using (a) conventional NFC and (b) proposed SNFC-GA.

B. Experimental realization

The efficacy of the proposed SNFC-GA-based linearized drive is tested and compared in real-time platform as shown in Fig. 1 using DSP2812 under load perturbation of 10 Nm by coupling a DC motor to an IM shaft. Fig. 12 reveals that the proposed SNFC-GA-based drive shows superior dynamic response and reduced ripples compared to the conventional NFC-based drive.

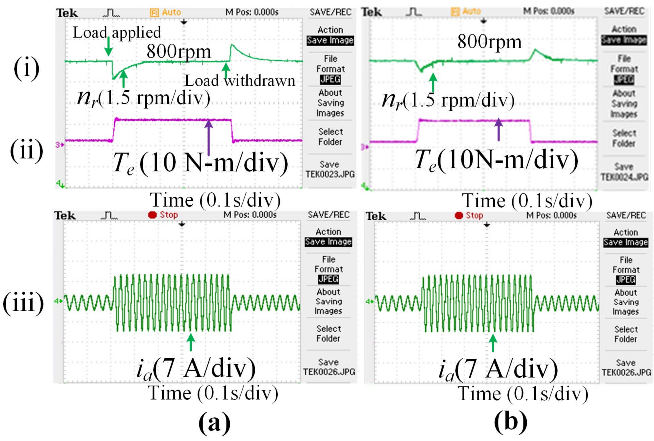

Fig. 12. Load perturbation responses of step increase of load to 50% using (a) conventional NFC, (i) speed (n_r), (ii) torque (T_e), and (iii) stator current (i_a), (b) proposed SNFC-GA, (i) n_r, (ii) T_e (iii) i_a.

TABLE I. SETTLING TIME RESPONSES OF IM DRIVE

Controller	Settling time (s)		
	Different time instants	***simulation***	***Experiment***
		$t_s(n_r)$	$t_s(n_r)$
Conventional NFC	0	0.79	
	1.5	1.6	1.62
	2	2.1	2.12
Proposed SNFC	0	0.86	
	1.5	1.63	
	2	2.13	
Proposed SNFC-GA	**0**	**0.84**	
	1.5	**1.57**	**1.6**
	2	**2.07**	**2.1**

V. CONCLUSION

The feedback linearized IM drive with the proposed SNFC-GA proves the robust and fast response with reduced speed and torque ripple. Apart from benefits of NFC, the proposed SNFC with GA has the advantage of optimal parameters selection obtained by GA. Furthermore, an experimental analysis has been carried out under load perturbation and the results provided and shown are closer to the simulated results. Moreover, it is evident from the comparative analysis data of Fig. 9 that the proposed SNFC-GA outperforms their counterpart with regard to dynamic as well as steady-state response. Thus, this robust performance of simplified NFC-GA is found to be suitable for realistic situation like high-performance industrial drive, robotics system, etc., where the control is more precise in spite of parametric uncertainties and load perturbation.

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APPENDIX A

MOTOR NOMINAL PARAMETERS

P_n = 3.7 kW, V_n = 415 V, n_r = 1445 rpm, f_n = 50 Hz, P = 2, R_s = 7.34 Ω, $L_{ls} = L_{lr}$ = 0.021 H, R_r = 5.64 Ω, L_m = 0.5 H, B = 0.035 kg-m^2/s, J = 0.16 kg-m^2.

APPENDIX B

CONTROLLERS PARAMETERS

Tuning rate of the weight ($\eta_{\omega i}$) = 0.05, tuning rate of the MFs (η_{ai}/ η_{bi}) = 0.005, sampling time for conventional NFC-based drive (T_s) = 250 μs, sampling time for proposed SNFC-based drive (T_s) = 100 μs, for SNFC-based drive: population size = 40, crossover rate = 0.8, mutation rate = 0.18, learning rate = 0.045, coefficient of momentum = 0.55.

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