$$u_N(n) = x_N(n-i) + \psi_N(n-1) * rs_N + y(n-1) * r_N \quad (10)$$

where rs_N is the self-feedback gain, r_N is the output feedback gain, N is the number of wavelon and i is the number of input delay. Now the output of the network is:

$$y = \sum_{N=1}^{N} w_N * \psi_N \quad (11)$$

where w_N is the output weight of the wavelon. The RWNN has been blended with IIR filter.

A wavenet is a topical network, where the output function is well localized in both frequency and time domains. In addition, another topical network can be accomplished to this wavenet architecture, as cascaded with a local IIR. The IIR filter function is to filter the wavelons that have "little" contribution to the identification process **[**21**]**. IIR filters are helpful for a high-speed design because they typically need a less number of multiplies compared to other filters. The general equation of an IIR filter can be written as [22]:

$$h_{(z)} = \frac{d_0 + d_1 z^{-1} + \cdots + d_N z^{-N}}{1 + c_1 z^{-1} + \cdots + c_M z^{-M}} \quad (12)$$

$$= \frac{\sum_{k=0}^{N} d_k z^{-k}}{1 + \sum_{k=0}^{M} c_k z^{-k}} \quad (13)$$

where c_k is the feed-forward filter coefficient, d_k is the feed backward filter coefficient, M and N are the maximum filter order. In order to perform this filter the following equation of the output approximation $\hat{y}(t)$ is required:

$$\hat{y}(t) = \sum_{i=0}^{M} c_i y(t-i) + \sum_{j=1}^{N} d_j \hat{y}(t-j)\, v(t) \quad (14)$$

Figure 5 shows the wavenet in cascading with IIR filter, where y(t) is the output of the wavenet and v(t) is the co-input is kept small for the purposes of stability feedback.

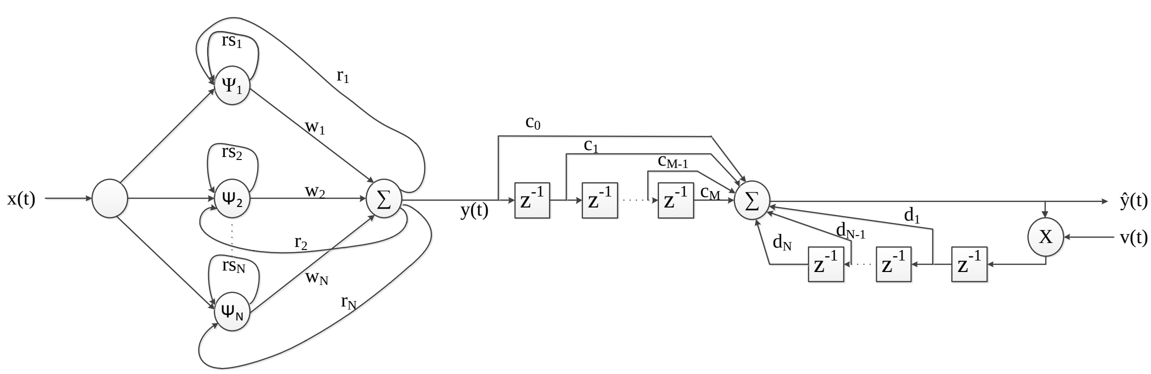

Figure 5: Wavenet based IIR filter configuration

PROPOSED BLDC MOTOR SPEED CONTROL BASED ON MRPID WITH WAVENET AND IIR FILTER

The BLDC motor is a non-linear system and multi-variable, so it is troublesome to get a favorable result using MRPID controller alone. Here will present the combination between that's controller and the wavenet. The wavenet is built as the on-line reference model of the BLDC motor and the MRPID controller get on-line tuning of its parameters by an auto-tuning algorithm.

Figure 6 shows the schematic diagram of the BLDC motor speed control based on MRPID with wavenet identification. The overall system has three stages to manipulate the speed of the BLDC motor in the desired way. The first stage is the completed wavenet with IIR filter, this stage required the input u(t) as the controlling signal to the BLDC motor and the wavenet output is the estimation reference speed $\hat{n}(t)$; the estimation error $\hat{e}(t)$ is defined as:

$$\hat{e}(t) = n(t) - \hat{n}(t) \quad (16)$$

where n(t) is the output speed of the BLDC motor. The second stage is the MRPID controller which has the speed error signal e(t) as the input and the control signal u(t) as the output to manipulate the BLDC motor speed. The third stage is the auto-tuning of the MRPID controller gains.

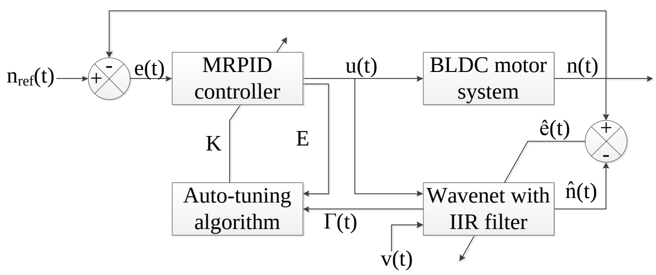

Figure 6: Schematic diagram for BLDC motor speed control based on MRPID controller with wavenet

The parameters of the wavenet are minimized by a cost function using invasive weed optimization based on the least mean squares (LMS) as:

$$\text{Cost function} = \frac{1}{2}\hat{e}(t)^2 \quad (17)$$

In order to tune the PID parameters use the following equations [21, 23]:

$$k_p(t) = k_p(t-1) + \mu_p * \hat{e}(t) * \Gamma(t) * (e(t) - e(t-1)) \quad (18)$$

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$$k_i(t) = k_i(t-1) + \mu_i * \hat{e}(t) * \Gamma(t) * e(t) \qquad (19)$$

$$k_d(t) = k_d(t-1) + \mu_d * \hat{e}(t) * \Gamma(t) * (e(t) - 2e(t-1) + e(t-2)) \qquad (20)$$

where $\mu_{p,i,d}$ are the learning rate of that gains which will be optimized using IWO algorithm, e(t) is the tracking speed error which is the difference between the reference speed $n_{ref}(t)$ and the actual speed n(t), and Γ(t) is parameter estimated by the wavenet as[21]:

$$\Gamma(t) = \sum_{i=0}^{M} c_i * y(t-i) \qquad (21)$$

where M is the order number of the IIR filter, c is the feed-forward coefficient of the IIR filter and y(t) is the output of the wavenet as described previously.

INVASIVE WEED OPTIMIZATION TECHNIQUE

The algorithm of Invasive Weed Optimization (IWO) was presented firstly 2006 by Mehrabian and Lucas [24]. It is easy and simple to program and understands and also has robustness and rapid global searching ability. So it is a convenient emulator for other evolutionary algorithms to be applied in many engineering fields [25, 26]. Over the specified area a finite number of seeds are being spread, any seed produce a new weed and then the weed will produce other weeds from its seeds depending on its fitness. The computational experiments show that the IWO is a highly competitive property where it is able to find the best and optimal solutions for the instances studied [27].

The Algorithm for Invasive Weed Optimization. The unwanted growing plants are called weeds, which have adaptive and robust nature. That will turn them into unfavorable plants in agriculture. A common agronomy belief is that “The Weeds Always Win”. The motivated new algorithm is colonization of invasive weeds by a common agriculture phenomenon. Figure 7 shows the algorithm flow chart. The specifics of the IWO are classified as follows:

A. Commence. Weeds are generated randomly over the search space as the inhabitance of initial solution.

B. Estimation. Calculate the fitness of each weed in the inhabitance of the controller parameters.

C. Propagation. The best weed’s fitness in the population will produce more seeds while the worst weed’s fitness will produce fewer seeds depending on the response of the BLDC motor variables. The increase of seeds number produced is linear based on weeds’ fitness depending on the following formula:

$$weed_{num} = S_{min} + (S_{max} - S_{min}) \frac{f - f_{worst}}{f_{best} - f_{worst}} \qquad (22)$$

where $weed_{num}$ is a number of weeds, S_{max}, S_{min} are maximum and minimum seeds respectively, f is the current fitness of the weed and f_{best}, f_{worst} are the best and the worst fitness of the current inhabitance.

D. Spatial Dispersal. Here weed will generate seeds around it leading to a local search for each plant. According to a normal distribution with mean equal to zero and variance σ^2, the produced seeds are randomly spread out around the parent weed to generate new controller gains. However, standard deviation σ of the random function will be reduced from a previously defined initial value $\sigma_{initial}$ to a final value σ_{final} in every generation As a function of iteration (iter.) as:

$$\sigma_{cur} = \sigma_{final} + (\sigma_{initial} - \sigma_{final}) \frac{(iter_{max} - iter)^n}{(iter_{max})^n} \qquad (23)$$

where σ_{cur} is the current standard deviation, $iter_{max}$ is the maximum number of iteration and n is the nonlinear modulation index. So that, σ determine weeds exploration ability. Therefore, exploration ability of all weeds is gradually reduced as iteration increases. At the end of the optimization process, the exploration ability has diminished so much that every weed can only find its position with respect to the smallest BLDC motor current and speed error.

E. Competitive Alienation. Through increasing of the iterations, the number of weeds in the colony will reach its maximum, and adopted the removal mechanism. The seeds and their parents are assorted together and only those with the best fitness of the BLDC motor output can stay live and become genital. Others are being removed.

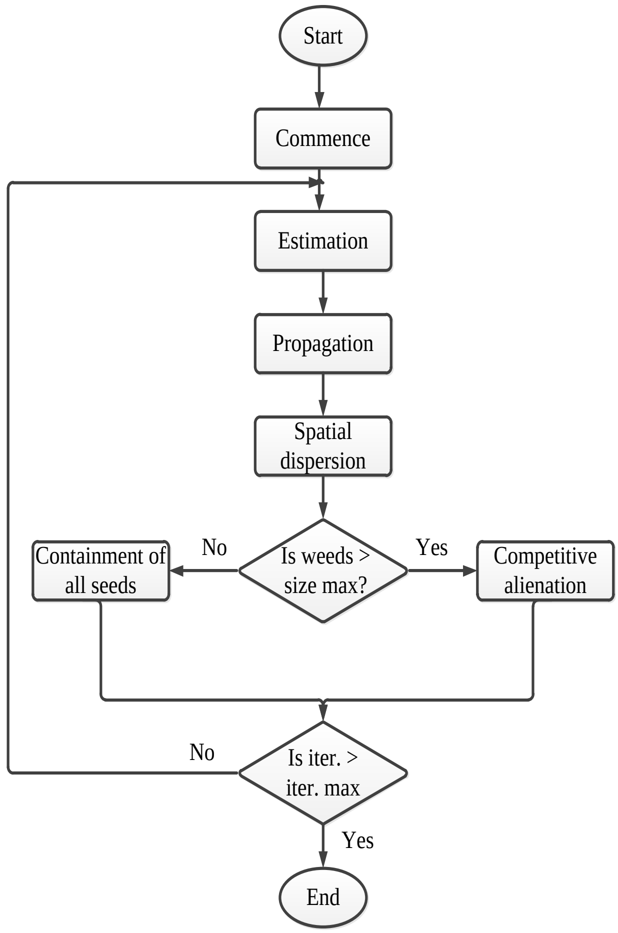

Figure 7: IWO flow chart

SIMULINK APPLICATION AND RESULTS

The plenary BLDC motor drive Simulink model has been performed using MATLAB/SIMULINK software. Each part of the BLDC motor drive model is finalized by a set of mathematical model. The motor parameters used here are shown in Table 1.

Table 1: Data of BLDC motor [28]

Parameter type	Parameter value	Unit
Rated power	1200	W
Rated voltage	76	V
Rated current	16	A
Rated torque	2.9	N.m
No load current	0.66	A
No load speed	3500	rpm
Torque constant	0.207	Nm/A
Voltage constant	0.207	V.s/rad
Terminal resistance	0.110	Ω
Inductance	0.6	mH
Viscous damping factor	$1.3\text{x}10^{-4}$	N.m s/rad
Rotor inertia	$1.7\text{x}110^{-3}$	kg.m^2
Number of poles	8	-

A. MRPID Controller

The multi-resolution analysis methods are used here to control speed and stator currents of the BLDC motor. From the schematic diagram in Figure 4, the Simulink model of the proposed MRPID speed controller is shown in Figure 8, where the speed error signal is the input to the S-Function block which has the MRA program. The decomposition program use Symlet with order 5 as the mother wavelet (sym5) as selected in the previous section and the decomposition level is second as it chose. The outputs of the S-Function block are the decomposition synthesis signals of the speed error signal which are multiplied by their corresponding gain before added them to generate the control signal. The values of the gains are optimized on-line using IWO algorithm. The MRPID current controller is building same as the speed controller as explained above.

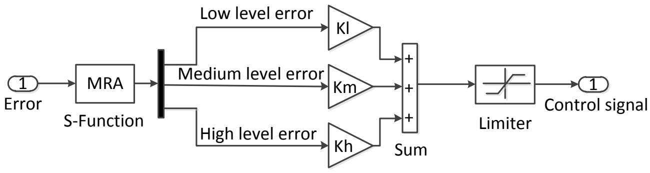

Figure 8: Simulink model of the proposed MRPID speed/current controller

The cost function used by IWO to optimize the parameters of the MRPID controllers as:

$$F = \min(\int e_s^2 dt + \int e_c^2 dt + M_p) \qquad (24)$$

where F is the fitness function, e_s is the speed error, e_c is the current error and M_p is the maximum overshoot. The most advanced control strategy is PWM control is selected. The IWO parameters are given in Table 2. These parameters are selected to obtain the optimal MRPID gains are shown in Table 3 to control the speed of the BLDC motor.

Table 2: IWO parameters

Parameter type	value
Number of initial plants	4
Maximum number of plants	100
Maximum iteration number	50
Maximum seeds number	5
Minimum seeds number	1
Initial standard deviation	10
Final standard deviation	0.0000001
Modulation index	3
Dimension	4

Table 3: MRPID optimized parameters

Parameters	Values
Speed controller	
High level (k_h)	7.28
Medium level (k_m)	0.4786
Low level (k_l)	0
Current controller	
High level (k_h)	15.48
Medium level (k_m)	84.71
Low level (k_l)	0

Figure 9 shows the speed response at the 2000 rpm reference speed starting with no load and the full load 2.9N.m is applied at 0.2 second. The electromagnetic torque, current phase i_a and line voltage v_{ab} at no load and full load are shown in Figures10 - 12 respectively.

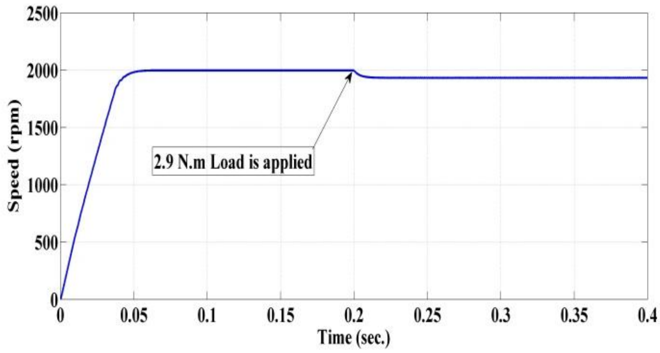

Figure 9: Speed response based on MRPID controllers

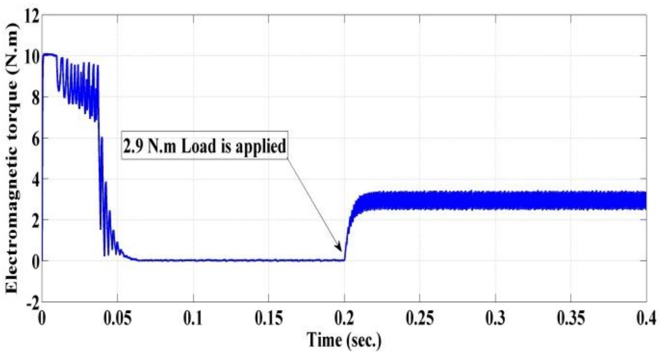

Figure 10: Electromagnetic torque based on MRPID controllers

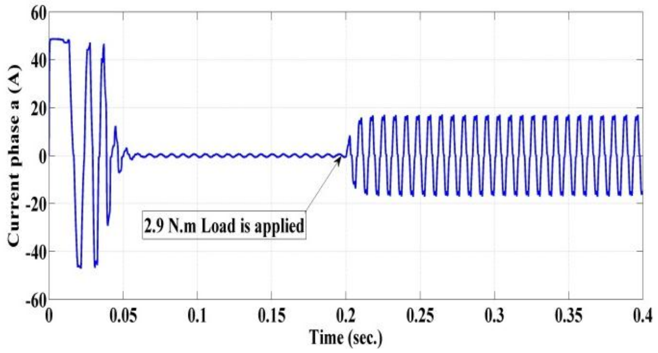

Figure 11: Current phase i_a based on MRPID controllers

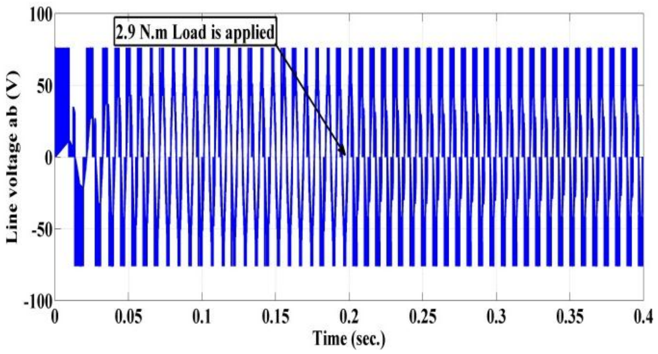

Figure 12: Line voltage v_{ab} based on MRPID controllers

The graphs obtained are given in Figures 9-12, shows the specific features of the BLDC motor by MRPID controller, i.e. smooth controlling that restraining harass and stress the engine. Also, the plant has better performance with low operating frequency. As the classical PID generates high-frequency may lead to rise the temperature and damage the actuator. The motor speed has flowed the reference speed with delay time about 0.06 second and the speed is reduced to a small amount through applied a full load, this will improve later.

B. MRPID Controller with Wavenet and IIR Filter

To overcome the decrease in speed in the previous section, Figure 13 below shows the Simulink model of the proposed BLDC motor speed control based on MRPID with Wavenet and IIR Filter. The reference model of the BLDC motor is built by the wavenet with IIR filter. The wavenet Simulink model is constructed from equations (2, 10 and 11). The neurons are built from the daughter wavelet that is generated from dilation a'th and translation d'th with the mother wavelet and self-feedback r'th and output feedback rr, each neuron is weighted by w'th gain. The wavelet mother function used here as the Mexican hat function. After trying and error the Mexican hat mother wavelet is more suitable to represent this model.

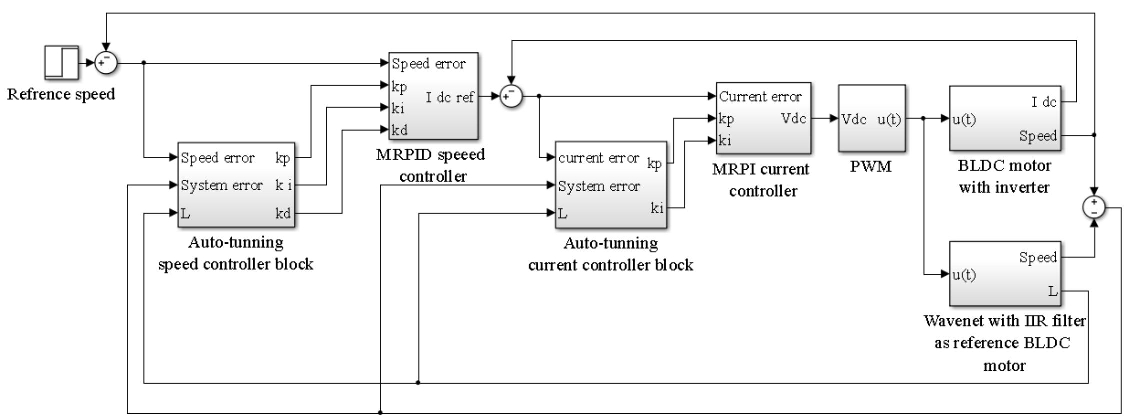

Figure 13: Simulink model of the proposed BLDC motor speed control based on MRPID with Wavenet and IIR Filter

The IIR filter Simulink model is constructed from equation (14) where the filter order M and N are kept to be 2 for both. The input to this model is the wavenet output and the estimation speed and Γ(t)(as equation (21)) are the output of that model. The auto-tuning Simulink model is constructed by using equations (18 - 20).

Firstly, the operation is done with MRPID controller without the auto-tuning stage to learn the reference BLDC motor. The parameters of the reference BLDC motor are optimized by using IWO algorithm based on the LMS as the cost function equation (17). The IWO parameters are same as shown in Table 2 but here with 23 dimensions. The wavenet optimized parameters are shown in Table 4 and the IIR filter optimized parameters are shown in Table 5. Secondly, the auto-tuning stage is performed and the learning rate parameters are optimized by the IWO algorithm as shown in Table 6.

Table 4: The wavenet optimized parameters

Wavenet Dilation Parameters				
a1	a2	a3	a4	
0.9684	1.654	6.377	0.05941	
Wavenet Translation Parameters				
b1	b2	b3	b4	
5.317	-1.429	0.5897	3.549	
Wavenet Weight Parameters				
w1	w2	w3	w4	
0.5566	-3.655	3.678	2.146	
Wavenet Feedback Parameters				
r1	r2	r3	r4	rr
1.244	0.8909	-1.102	0.4564	-0.04522

Table 5: The IIR filter optimized parameters

Feedforward Parameters			Feedback Parameters		Co-input
c0	c1	c2	d1	d2	v
2.724	2.831	2.724	0.1618	2.525	-0.3642

Table 6: The learning rate optimized parameters

Speed Controller			Current Controller	
μ_p	μ_i	μ_d	μ_p	μ_i
24.35	43.03	-12.71	-7.101	20.88

The simulation results are performed by applying all the above parameters to the BLDC motor drive model with the 0.4 second simulation time. Figure 14 shows the speed response at the 2000 rpm reference speed starting with no load and the full load 2.9N.m is applied at 0.2 second. The electromagnetic torque, current phase i_a and line voltage v_{ab} at no load and full load are shown in Figures 15-17 respectively.

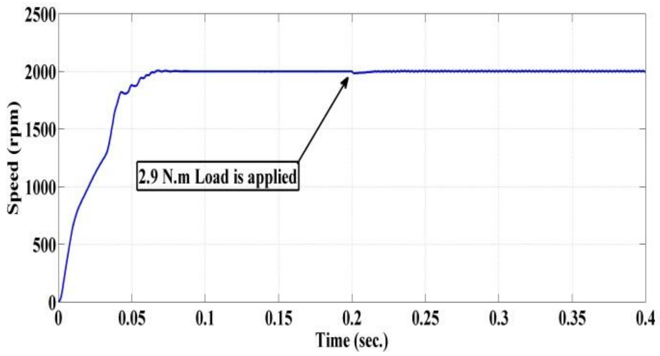

Figure 14: The speed response by on-line tuning controller based on wavenet with IIR filter

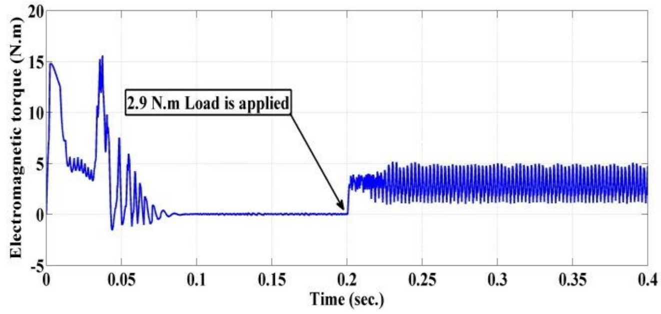

Figure 15: The electromagnetic torque by on-line tuning controller based on wavenet with IIR filter

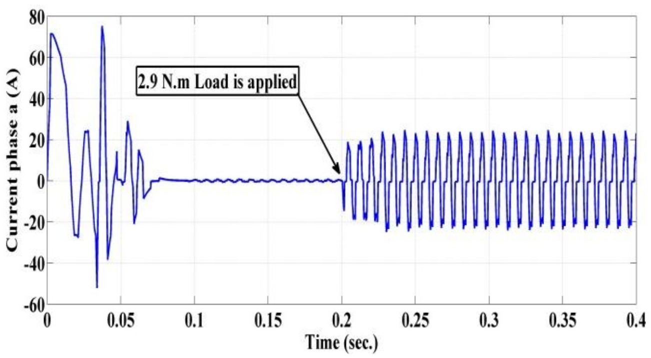

Figure 16: The current phase i_a by on-line tuning controller based on wavenet with IIR filter

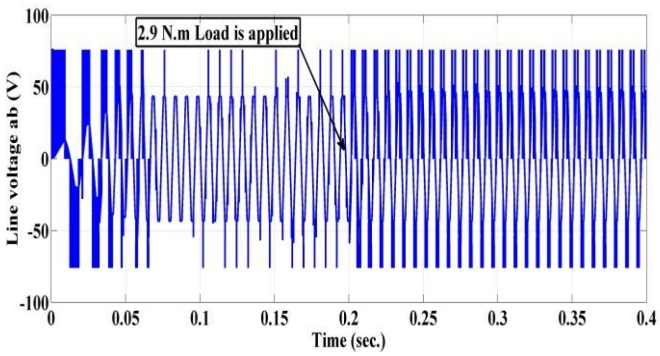

Figure 17: The line voltage v_{ab} by on-line tuning controller based on wavenet with IIR filter

From results above can be seen that the speed has good response with removing the decrease after loading and the other machine variables are stable with that proposed controller. Another merit is that the control signal characteristics generate a soft control even in the presence of noise.

COMPARISON BETWEEN CONTROLLING METHODS

The comparison is done with respect to the operation and results from the output waveforms of the performing models as shown in Table 7 below.

Table 7: Comparison between controlling methods

Feature	MRPID controller	Wavenet with PID controller
Rise time	0.06	0.07
Steady-state error at no load	0.15%	0%
Maximum Overshoot	0%	0.35%
Overcome Load	poor	Very good
ripple	Smooth	Jagged
Speed decrease with full load	Yes	No

While the classical PID has simple hardware structure as compared with proposed MRPID, it does not have enough flexibility to control the nonlinear system and generate high frequency may lead to rise the temperature and damage the actuator.

Actually, the proposed wavenet method has complex hardware structure but it gives a better load rejection.

CONCLUSION

In this paper, the wavelet decomposition approach is used to produce modified advanced controller called MRPID controller. This is used to control the BLDC motor speed and current and can provide better performance of the motor variables than the classical controller. The current controller was setting the current and overcome the high starting current. Also, this paper achieved on-line control and on-line identification by using wavenet with IIR filter approach. The benefit of the proposed methods is to reach a better response of the speed. A proposed wavenet method is a modified method of a MRPID in terms of overcoming the load rejection and good robustness system for future BLDC motor change parameters. The parameters of controllers are optimized using IWO algorithm which given optimal value with stable operation. Also, the BLDC motor mathematical representations are performed by using Matlab simulation. The results of different BLDC motor variables are plotted and discussed.

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