MODELING AND FIELD ORIENTED CONTROL OF INDUCTION MOTOR BY USING AN ADAPTIVE NEURO FUZZY INTERFERENCE SYSTEM CONTROL TECHNIQUE

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Abstract- This paper presents the implementation of an adaptive neuro fuzzy interference system (ANFIS) technique for controlling the speed of the induction motor. The proposed controller is the combination of Artificial Neural Network (ANN) and Fuzzy Logic Controller (FLC). The ANN used for determining the appropriate inputs to control the system and FLC is an intelligent controller used for analyzing the system control inputs in terms of logic variables. In the proposed control scheme, the speed variation of the motor will be measured from the rotor shaft position. Because, in field oriented control scheme, the rotor shaft position ensures the speed range behavior of the motor. In direct torque control (DTC), the actual torque and the change of torque of the induction motor is applied to the ANFIS. From the output of ANFIS, the control electromagnetic torque value is obtained and the speed of the motor is controlled. The proposed control technique is implemented in MATLAB/SIMULINK platform and the output performance will be evaluated. The proposed ANFIS based DTC speed control technique is compared with PI controller and fuzzy controller.

Keywords- ANFIS, DTC, Fuzzy, Induction Motor, PI Controller.

I. INTRODUCTION

Induction Machine is an important class of electric machines which finds wide applicability as a motor in industry. An Induction Motor (IM) is an AC motor, where power is supplied to the rotor by means of electromagnetic induction. The IM, especially the squirrel-cage type, is widely used in electrical drives. Generally, variable-speed drives for induction motors require both wide operating range of speed and fast torque response, regardless of load variations. IMs are used mainly for constant-speed applications. To improve the motor efficiency, the flux must be reduced by obtaining a balance between copper and iron losses. The control and estimation of IM drives constitute a vast subject and these IM drives have been the work horses in the industries for variable speed application that covers from fractional horse power to multi Mega-watt power. The variations of electrical parameters, the inaccuracy of estimated fluxes will degradation the speed control performance. The control of IM is complex due to its nonlinear nature, and the parameters change with operating conditions. Speed estimation is an issue of particular interest with induction motor drives, where the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field.

Direct Torque Control (DTC) technique controls the torque and speed of the motor, which is directly based on the electromagnetic state of the motor. The name direct torque control is derived from the fact that on the basis of the errors between the reference and the estimated values of torque and flux it is possible to directly control the inverter states in order to reduce the torque and flux errors within the permissible limits. The main advantages of DTC are robust and fast torque response, no requirements for coordinate transformation, requirements for PWM pulse generation and current regulators. The DTC method is a simple and give fast transient response against the speed changes of motor, hencemost of the industrial drives are equipped with DTC. The different induction motor control techniques such as DTC with space vector modulation (SVPWM) technique, artificial intelligence techniques etc. were in development currently. The present paper concerns with the implementation of Fuzzy and ANFIS techniques to improve the speed/torque characteristics of the induction motor.

II. MATHEMATICAL MODEL OF DTC OF INDUCTION MOTOR

The mathematical model of the induction machine is used for analyzing the dynamic behavior of the motor. The change in the dynamic behavior of the motor affects the motor parameters such as speed, torque, resistance, flux and etc. So, the dynamic model is needed for analyzing the change inperformance of the induction motor. The dynamic model of the induction motor is derived by transforming the three phase quantities into two phase direct and quadrature axes quantities. The mathematical equation of DTC of the induction motor is given below.

2.1 Voltage equations:

$$V_{s\alpha} = r_s i_{s\alpha} + P\psi_{s\alpha} \quad (1)$$

$$V_{s\beta} = r_s i_{s\beta} + P\psi_{s\beta} \quad (2)$$

$$V_{r\alpha} = r_r i_{r\alpha} + P\psi_{r\alpha} + \psi_{r\beta}\omega_r \quad (3)$$

$V_{r\beta} = r_r i_{r\beta} + P\psi_{r\beta} - \psi_{r\alpha}\omega_r$ (4)

Where, $\psi_{s\alpha} = \psi_{r\alpha} = i_{r\alpha}L_r + i_{s\alpha}L_s$ and

$\psi_{s\beta} = \psi_{r\beta} = i_{r\beta}L_r + i_{s\beta}L_s$.

These stator flux equations are rewritten as following them,

2.2 Stator Flux:

$\psi_{s\alpha} = \int (V_{s\alpha} - r_s i_{s\alpha})dt$ (5)

$\psi_{s\beta} = \int (V_{s\beta} - r_s i_{s\beta})dt$ (6)

The magnitude of the stator flux (ψ_s) is the combination of $\alpha - \text{axis}$ and $\beta - \text{axis}$ flux which is expressed as follow,

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 - \psi_{s\beta}^2} \quad (7)$$

The magnetic track phase angle (θ) is expressed as follow,

$$\theta = \arctan\left(\psi_{s\alpha} / \psi_{s\beta} \right) \quad (8)$$

Where, $V_{s\alpha}$, $V_{s\beta}$, $V_{r\alpha}$ and $V_{r\beta}$ are the $\alpha - \text{axis}$ and $\beta - \text{axis}$ voltages of stator and rotor respectively. Then, $i_{s\alpha}$, $i_{s\beta}$, $i_{r\alpha}$ and $i_{r\beta}$ are the $\alpha - \text{axis}$ and $\beta - \text{axis}$ currents of stator and rotor respectively. The resistance and inductance of the stator and rotor winding are denoted as r_s, r_r, and L_r respectively. The stator and the rotor flux of the motor are described as $\psi_{s\alpha}$, $\psi_{r\alpha}$, $\psi_{s\beta}$ and $\psi_{r\beta}$ respectively.

The electromagnetic torque of the motor is obtained from the inductance and the $\alpha - \beta$ axis current. The $\alpha - \beta$ axis current of the motor is obtained from the flux linkages that occurred in the stator and rotor of the motor. The expression of the electromagnetic torque that is produced by the motor is given as follows.

2.3 Electromagnetic Torque:

$T_e = 3/2 \cdot P/2 \left(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}\right)$ (9)

The actual torque developed by the motor in terms of rotor speed is illustrated as follow.

$T = T_e - T_L = J\frac{d\omega_r}{dt} + B\omega_r$ (10)

Where, P is the number of poles,

J is the moment of inertia of rotor,

B is the damping coefficient,

ω_r is the rotor speed,

T_L is the load torque,

T_e is the electromagnetic torque.

2.4 Vector Diagram:

Considering the vector diagram (Figure 1), the two stator phase currents(i_b and i_c). Here, the two phase currents are required, as the third one (i_a) can be derived from the assumption that the three phase currents are 120 electrical degrees apart and instantaneously add to zero. The three currents are then converted to a two-phase orthogonal system with axes α and β by means of a technique called the Clarke Transformation. For simplicity, axis α can be made equal to axis a. The two orthogonal currents i_α and i_β are then transformed to a time-invariant, rotating orthogonal system represented by the field and torque components d and q of the equivalent rotor currents id and iq. The α/β coordinate frame is rotated counterclockwise to line up with the rotor flux axis ψ_r. The angle of rotation (θ) is determined with the aid of the motor model. The vector diagram of flux linkages in the stator and rotor winding is illustrated as following them.

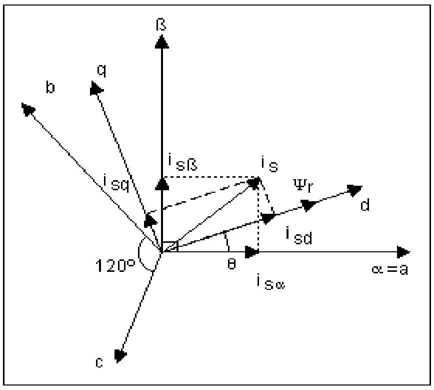

Figure 1: Vector Diagram of DTC of Induction Motor.

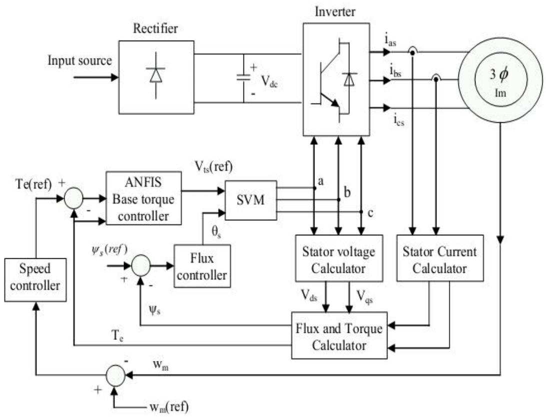

Figure 2: Proposed ANFIS Based DTC System.

In Figure 2, the control structure of proposed ANFIS is easily described. In the proposed model, the actual torque (T_e^*) and change of torque (ΔT_e^*) values are determined. The reference values of the torque are varied by the variation of load variation so, it's necessary for optimize reference torque. Then, the change of torque is determined from the torque deviated from the reference torque of the system. These actual torque and change torque is applied to ANFIS and the controlled output is determined. Based on the controlled output, the PWM control signal is generated for controlling the inverter gate. Here, the space vector PWM modulation technique is used for determining the gate control signal. The SVM based switching table is referred from switching output, the IGBT gate is controlled. Then, the detailed description of ANFIS will be discussed in the following section.

III. ADAPTIVE NEURO FUZZY INTERFERENCE SYSTEM

Adaptive neuro-fuzzy inference system is the combination of neural network (NN) and fuzzy logic controller (FLC). This hybrid combination enables to reduce the complexity of power intelligent system. In ANFIS, the fuzzy inference system is implied through the structure and neurons of the feed forward adaptive neural network. Here, the electromagnetic torque of the motor is controlled by the values of actual torque and change of torque of the motor. In the hybrid system, the data set is developed by neural network in terms of actual torque and change of torque and reference torque of the motor. The generated data set is fed to fuzzy interference system and the fuzzy control rules are generated. This adaptive system is generated by two phases one is training phase and other is testing phase. The training and testing phase are explained by following them.

3.1 Training Phase:
The first phase of ANFIS is training phase which used for generating training data set. In the proposed control approach, the actual torque and change of torque of the motor values are generated in the form of vector and the data is applied to the neural network. Then, the data is trained by back propagation training algorithm with respect to the actual torque of motor. Then, the trained data is applied to the fuzzy interference system for generating the control fuzzy rules. In ANFIS, the fuzzy rules base control interference system is automatically generated.

3.2 Testing Phase:
The next phase of ANFIS is testing which used for creating the tested speed control system model. In the testing phase, the actual torque and the change of torque of the motor is applied as the input, the appropriate control electromagnetic torque is obtained from the interference system.

3.3 Features of ANFIS
In the proposed speed control system, the ANFIS is used for the set of features which is based on neural network and fuzzy system. The feature of the neural network is the structure network of feed forward type and the network training algorithm is back propagation. In the back propagation training algorithm, the data is trained based on the network error. The error of the network is the difference between the target value and the actual value. Hence, the appropriate control model can be to developed. The model of proposed fuzzy interference systemis based on the Sugeno model which containing set of rules. The fuzzy concept consists of three steps i.e. fuzzification, rule base decision making and defuzzification. In the fuzzy process, the vector of the firing strengths is normalized and the resulting vector is defuzzyfied by utilizing the first order Sugeno model. The normalization processes consist of fuzzification and decision stage.

3.4 Structure of ANFIS:
The structure of ANFIS system consist of five layers which are categorized as input layer, input membership function layer, rule layer, output members function layer and output layer respectively. The fuzzy interference decision tree is to classify the data into one of 2^n(orP^n) linear regression models to minimize the sum of squared errors (SSE).

$$SSE = \sum_i er_i^2 \qquad (11)$$

Where, n is the number of input variables, P^n is the number of fuzzy divisions for each input variable and er_i^2 is the error between the desired and actual output respectively. The first order two input sugeno fuzzy model is given as in follow.

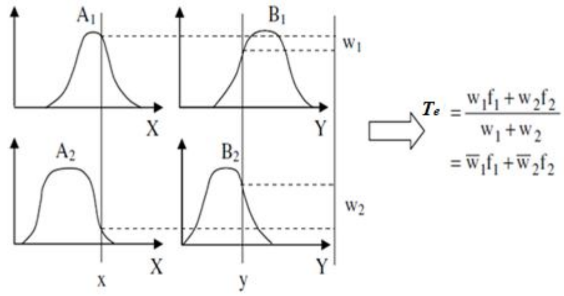

Figure 3: Two input first order Sugeno fuzzy model with two rules.

The typical fuzzy if-then rule set for the first orderSugeno fuzzy inference model, can be stated below,

If
x_1 is A_1 AND x_2 is B_1, then $f_1 = p_1 T_e^* + q_1 \Delta T_e^* + r_1$
If
x_1 is A_2 AND x_2 is B_2, then $f_2 = p_2 T_e^* + q_2 \Delta T_e^* + r_2$

Where, A_i and B_i are the antecedent fuzzy sets and parameters p_i , q_i and r_i are the fuzzy design parameters calculated during the training process (i=1, 2,…n). The two input and single output ANFIS structure is given as following them.

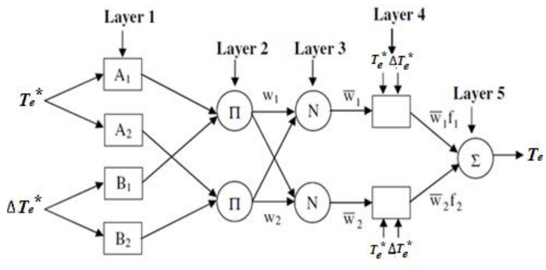

Figure 4: Structure of ANFIS.

In Figure 4, the mechanism for obtaining the actual torque (T_e) of the motor for a given input vector $[T_e^*, \Delta T_e^*]$ Sugeno model is illustrated. The structure of the ANFIS and the each layers are explained as following them.

Layer 1:In this layer, the adaptive nodes with node functions are consisted; the node function is defined as follow:

$O_i^{layer\ 1} = \mu_{A_i}(T_e^*)$(12)

$$O_i^{layer\ 1} = \mu_{B_i}(\Delta T_e^*) \quad (13)$$

Where, ω^* is the input to node i&A_i is the linguistic label related to that node function. The membership function $O_i^{layer\ 1}$ indicates the extent to which the specified T_e^* satisfies the quantifier A_i . Generally, a bell-shaped $\mu_{A_i}(T_e^*)$ that has a maximum of 1 and a minimum of 0 is considered which is shown below.

$$\mu_{A_i}(T_e^*) = \frac{1}{1+\left|\frac{T_e^*-c_i}{a_i}\right|^{2b_i}} = \exp\left\{-\left(\frac{T_e^*-c_i}{a_i}\right)^{2b_i}\right\} \quad (14)$$

Where, the parameter set $\{a_i, b_i, c_i\}$ which modifies the membership functions on linguistic label A_i is known as premise parameter. Similarly, the value of $\mu_{B_i}(\Delta T_e^*)$ is selected.

Layer 2: By multiplying the input signals and sending out the product by each node of the layer, the firing strength of the rule is calculated.

$$O_i^{layer\ 2} = w_i = \mu_{A_i}(T_e^*)\mu_{B_i}(\Delta T_e^*), i = 1,2 \quad (15)$$

Layer 3: The i^{th} node of this layer is used to determine the ratio between the firing strength of the i^{th} rule and the sum of firing strengths of all rules.

$$O_i^{layer\ 3} = \overline{w_i} = \frac{w_i}{w_1+w_2} \quad i = 1,2 \quad (16)$$

The output of this layer is denoted in terms of normalizedfiring strengths.

Layer 4: The involvement of i^{th} rule in the overall output is calculated by the i^{th} node of this layer as follows,

$$O_i^{layer\ 4} = \overline{w_i}f_i = \overline{w}_i(p_iT_e^*) + q_i\Delta T_e^* + r_i \quad (17)$$

Where, $\overline{w_i}$ is the output of layer 3 and $\{p_i, q_i, r_i\}$ are the parameter set of the layer 3. The term consequent parameters are used to indicate the parameters of this layer.

Layer 5: By taking the summation of all the inputs by the single node that exists in this layer indicated asΣ, the overall output is calculated.

$$\text{Overall output} = O_i^{layer\ 5} = \sum_i \overline{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (18)$$

For the ANFIS structure shown in Figure 4, the fact that the overall output f can be expressed as a linear combination of the consequent parameters for the case of fixed premise parameters is a most evident from. The output of Figure 4 can be represented more precisely as,

$$T_e = \overline{w}_1 f_1 + \overline{w}_2 f_2 \quad (19)$$

$$\text{i.e } T_e = (\overline{w}_1 T_e^*)p_1 + (\overline{w}_1 \Delta T_e^*)q_1 + (\overline{w}_1)r_1 + (\overline{w}_2 T_e^*)p_2 + (\overline{w}_2 \Delta T_e^*)q_2 + (\overline{w}_2)r_2 \quad (20)$$

In the proposed control system, the ANFIS structure is trained by giving the vector as input. Then, the appropriate control output is applied SVM for generating control signal. The generated control signal is applied to the inverter and control the speed of induction motor.

IV. SIMULATION

The proposed ANFIS based hybrid DTC technique was implemented in MATLAB working platform. Then, the speed control performance of proposed control technique was tested with induction motor 2.2Kw/400V. The speed control performance of proposed control technique was compared with PI controller and fuzzy controller. From the developed model, the speed, torque, current, flux and d-q axis voltage were analyzed. The simulink model of proposed speed control system and PI control system were illustrated in Fig.5 and Fig.6 respectively. The implementation parameters of proposed model is described in following them,

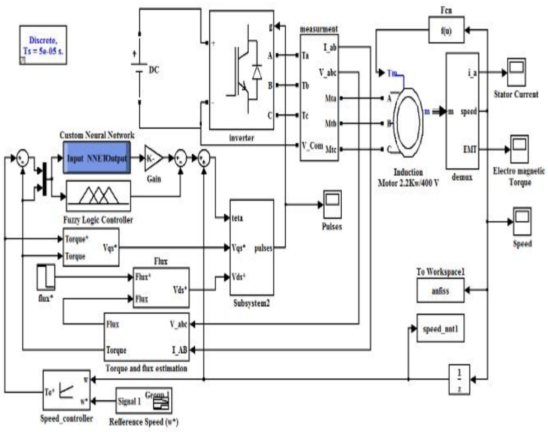

Figure 5: Simulink Model of Proposed Speed control System.

V. RESULTS AND DISCUSSION

From the above Simulink model, we described the dynamic response of the IM when the speed set point is 80 rad/sec from rest at the duration of 0.5 sec. Then the speed set point is varied from 80 rad/sec to 60 rad/sec at duration of 0.5 sec. After that the speed set point is varied from 60 rad/sec to 100 rad/sec at duration of 1sec. The performance of current, voltage, flux, torque, speed and comparison of speed are depicted from Fig. 6 to Fig. 11.

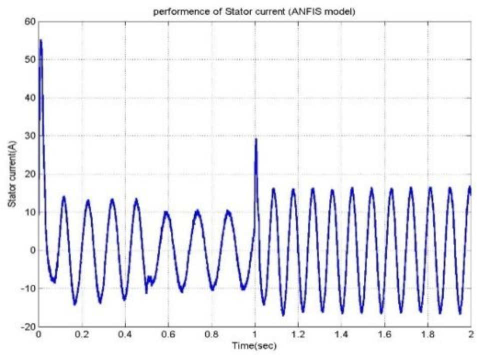

Figure 6: Dynamics of Stator Current.

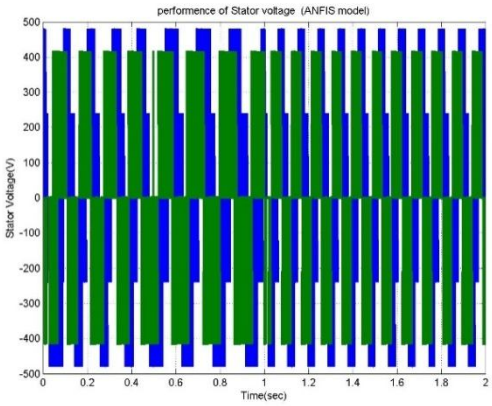

Figure 7: Transformed d-q axis of Stator Voltage.

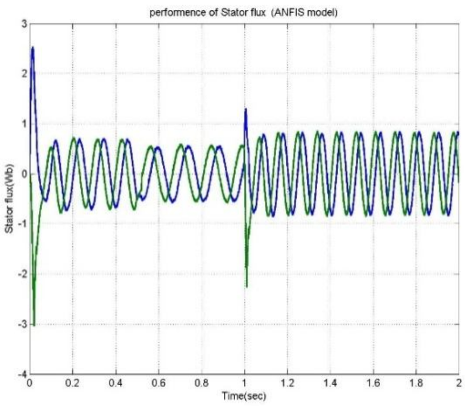

Figure 8: Dynamics of d-q axis Stator Flux.

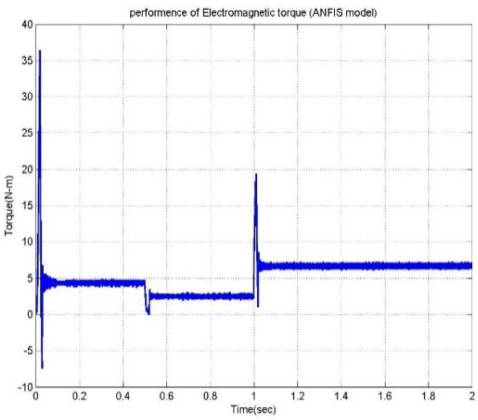

Figure 9: Variations of Electromagnetic Torque.

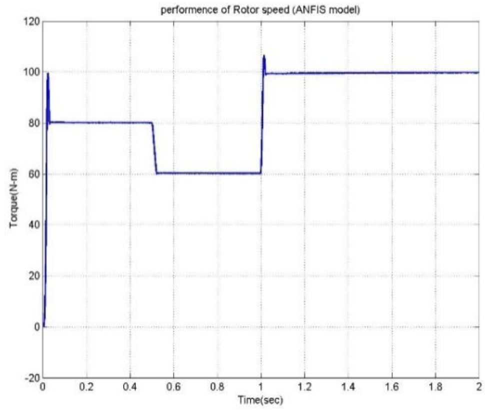

Figure 10: Performance of Speed.

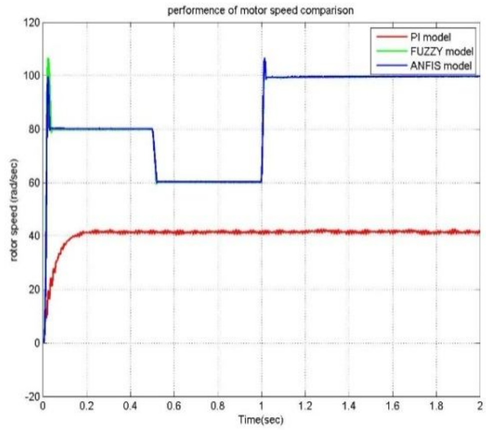

Figure 11: Comparison Performance of Rotor Speed.

In Figure 11, the comparison performance of proposed ANFIS speed controller, the PI speed controller and the fuzzy speed controller are described. From the comparative analysis, the proposed ANFIS speed controller provides smooth speed control performance when compared to other two controllers. The fuzzy controller offers high overshoot, oscillation and the PI controller is does not reach the steady state set speed. Hence, the proposed ANFIS speed controller is better than PI and fuzzy speed controllers.

CONCLUSION

The proposed ANFIS based DTC method was implemented in MATLB working platform. Then, the performance of the proposed control technique was tested with induction motor. The mathematical model of the induction motor was analyzed in terms of stator voltage equation and torque equation. The actual torque and the change of toque of the motor were applied to the ANFIS and the electromagnetic torque was determined from the output of interference system. The output of ANFIS was converted into stator voltage and the stator voltage was applied SVM. From the output of SVM, the control signal was generated ad control the speed of the motor close to set speed. Then, the performance speed and the torque are analyzed and the analyzed performances are compared with PI controller and fuzzy controller. From the comparative analysis, the proposed ANFIS speed control technique is better than other control techniques.

APPENDIX-A

Table I: Implementation parameters.

Parameters	Values
Nominal power	2200 watts
Line to line voltage	400 volts
Frequency	50 Hz
Stator resistance	3.67 ohm
Stator inductance	0.0269 H
Rotor resistance	2.1 ohm
Rotor inductance	0.0269 H
Mutual inductance	0.0324 H
Inertia	0.0155 kg.m^2
Friction	0.0025 N.m.s
Number of poles	2

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