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Research Article

Overvoltage Analysis of PWM Inverter Fed Induction Food Motor with Long Cable

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Abstract: By analyzing overvoltage at food motor end, it is determined that the inverter output (rise/fall time of voltage pulse), the nondestructive cable parameters (inductance, capacitance and length) and the characteristic impedance of food motor are the main influence factors affecting overvoltage at food motor end in PWM inverter fed induction food motor system. Mathematic formulas and simulations for factors are carried out firstly and then the weight of every factor is determined based on the BP neural network. All the study in this study has certain guiding significance for the analysis and design of PWM inverter fed induction food motor system.

Keywords: BP neural network, food motor, PWM inverter

INTRODUCTION

The rapid development of power electronic devices and the application of PWM (Pulse Width Modulation) technology promote widespread use of the inverter fed induction food motor system in many aspects, which has already brought remarkable economic efficiency and energy-saving effect (Akagi and Shimizu, 2008). The increase of PWM carrier frequency and the high-speed switching effect of power electronic devices will produce remarkable negative effects for PWM driven system (Adabi and Vahedi, 2013; Bell *et al*., 2001; Shami and Akagi, 2010). For example, fast turn-on and turn-off of inverter switch components will produce high dv/dt, which can cause great impact on the motor and also generate strong EMI (Electromagnetic Interference) (Akagi and Doumoto, 2004); When the food motor and the inverter are connected with a long cable, the impedance mismatch issues between food motor and cable will appear, which can bring about overvoltage and high-frequency damping oscillation (Liu *et al*., 2011; Jiang *et al*., 2013; Moreira *et al*., 2003), accelerating food motor aging and even resulting in food motor burnout and cable blowout.

Many scholars and researchers have already conducted in-depth study for overvoltage at food motor end in theory and experiment. Tilea and Munteanu (2013) have made detailed simulation analysis for food motor end overvoltage caused by cable parameters. Ma *et al*. (2001) and Vaishnavi *et al*. (2013) have worked on voltage reflection phenomenon on cable in the PWM inverter fed induction food motor system. Wan *et al*. (2001) has carried out the negative effect of high-frequency PWM voltage pulse on food motor. The researches aforementioned all concentrate on one respect that affect overvoltage at food motor end. Nevertheless, there is lack of systematic research for the factors affecting overvoltage at food motor end.

Based on the research of predecessors, this study studies overvoltage at food motor end caused by the inverter output (rise/fall time of voltage pulse), the nondestructive cable parameters (inductance, capacitance and length) and the characteristic impedance of food motor in theory and simulation systematically and the weight of every influence factor is determined by the BP neural network. The research content in this study will not only help people understand overvoltage issues in PWM inverter fed induction food motor system, but also have certain guiding significance for the design of inverter system (Zhang *et al*., 2012).

MATERIALS AND METHODS

The overvoltage analysis at food motor end: Transforming between each instantaneously effective switch mode, the inverter can be equivalent to a single-phase model, as shown in Fig. 1. The inverter output can be seen as a PWM voltage pulse generator, while RC, CC and LC signify the resistance, capacitance and inductance of connection cable, respectively. ZR is the characteristic impedance of motor, which is constant when the food motor speed is fixed.

When the frequency is high, there will be impedance mismatch if the characteristic impedance of inverter to the food motor by long cable, while

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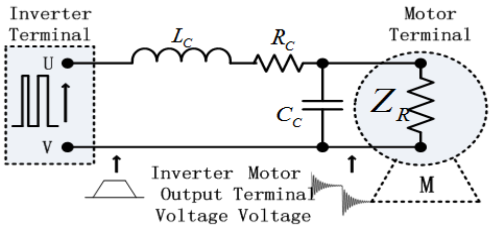

Fig. 1: The single-phase equivalent model of PWM inverter

food motor is much greater than the characteristic the impedance of cable. PWM voltage pulses travel from reflection waves move towards the inverter due to the voltage reflection caused by the cable impedance and food motor impedance at the end of the cable. Thus the superposition of PWM pulses and reflection waves will make voltage amplitude at food motor end higher than the PWM pulse amplitude. When the cable length is I, at the time t = τ, the ling-to-line voltage at food motor end can be expressed as:

$$V(l,\tau)=\frac{Z_C}{Z_C+Z_S}V_S(1+K_R) \tag{1}$$

where,

Z_S, Z_C : Represent the cable impedance and the inverter impedance and if the cable is nondestructive, $Z_C = \sqrt{\frac{L_C}{C_C}}$

V_S : Voltage pulse of the PWM inverter output

$K_R = \frac{Z_R - Z_C}{Z_R + Z_C}$: The voltage reflection coefficient at food motor end

The characteristic impedance of inverter is relatively small which can be ignored generally. Because of Z_C, = Z_R, there can be got $V(I, \tau) \approx 2V_S$, thus the overvoltage at food motor end can be as high as twice of the PMM voltage pulse, which can easily leads to rapid deterioration and even permanent damage of food motor insulation.

In the conventional analysis, voltage pulses of PWM inverter output are treated as ideal step signals, which in practice are trapezoidal waves with certain rise/fall time. The rise/fall time of voltage pulses have influence on traveling wave reflection on cable. Consider the rise/fall time of PWM voltage pulses, the voltage $U_{motor}(t)$ can be expressed as:

$$U_{motor}(t)=\sum_{k=0}\frac{U_0}{t_r}(1+K_R)[(t-(2k-1)\tau)\cdot U(t-(2k-1)\tau) -(t-(2k-1)\tau-t_r)\cdot U(t-(2k-1)\tau-t_r)] \tag{2}$$

where,

U_0 = The voltage pulse
U (t) = The unit step function
t_r = The rise time of PWM pulse
k = The reflection times of voltage pulse on the cable
τ = The one-way delay time on the cable given by:

$$\tau = 1/\nu = \sqrt{L_C C_C} = \frac{c}{\sqrt{\varepsilon}} \tag{3}$$

In Eq. (3), the cable is isolated (μ = 1), ν is the propagation speed for pulse in nondestructive cable, c is the velocity of light and ε is the relative dielectric constant. The oscillation cycle of line-to-line voltage can be calculated in Eq. (4):

$$T_{cycle} = 4\tau = \frac{4l}{\nu} = 4l\sqrt{L_C C_C} \tag{4}$$

Summarizing the analysis given above, it can be determined that the voltage at food motor end is affected by inverter output (rise/fall time of PWM pulses), the parameters of nondestructive cable (capacitance, inductance and length) and the characteristic impedance of motor.

The simulation of overvoltage at food motor end: In the following part, the simulation model of single-phase PWM inverter system based on Fig. 1 is built on MATLAB/SIMULINK (Fig. 2) and the detailed simulation results for different parameter values are also presented. In the simulation, the characteristic impedance ZS of PWM inverter is 0.5 Ω, the amplitude US of PWM pulse is 500 V and the frequency of voltage pulse is 500 Hz.

The PWM inverter output pulse influence on line-to-line voltage at food motor end: The value of cable parameters are as follows:

R_C = 0.02 Ω/km
L_C = 1 mH/km
C_C = 10 nF/km
l = 0.5 km

The characteristic impedance Z_R of food motor is 5 kΩ. Take the rise/fall time t_r/t_f to 1, 5 and 10 usec, respectively. The simulation results are shown in Fig. 3.

It can be concluded from Fig. 3 that when the switch frequency, cable parameters and food motor impedance are same, the longer the rise/fall time of PWM pulse, the smaller the voltage amplitude at food motor end, thus the smaller the overvoltage hazards. Combined with Fig. 3 and Eq. (4), it can be learned that overvoltage oscillation cycle has nothing to do with food motor impedance, but the oscillation duration become shorter.

The cable parameters influence on line-to-line voltage at food motor end: The characteristic impedance Z_R of food motor is 5 kΩ and the rise/fall time t_r/t_f is 1 usec; the value of nondestructive cable parameters are as follows:

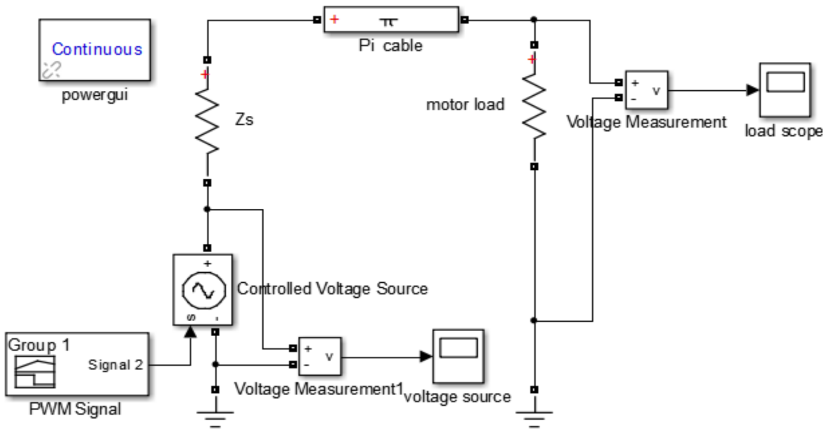

Fig. 2: The simulation model of single-phase PWM inverter

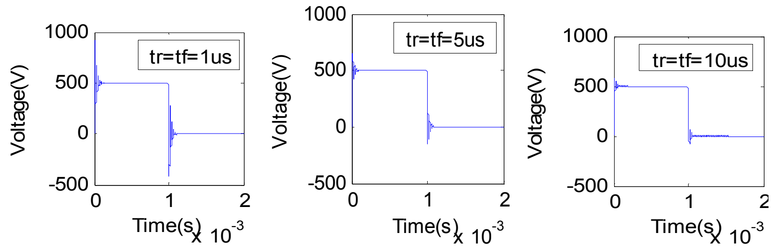

Fig. 3: The simulation results of different rise/fall time

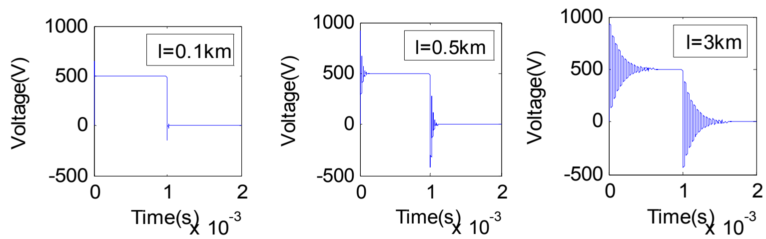

Fig. 4: The simulation results of different cable length

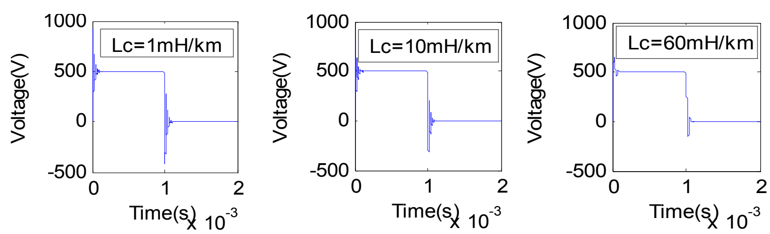

Fig. 5: The simulation results of different cable inductance

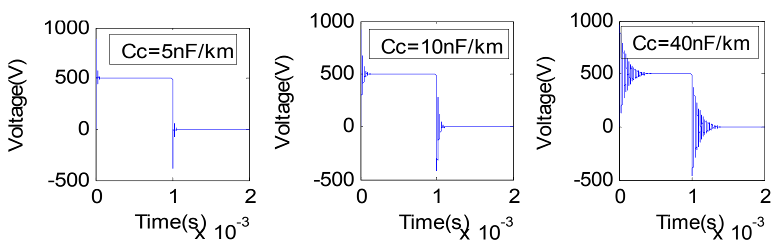

Fig. 6: The simulation results of different cable capacitance

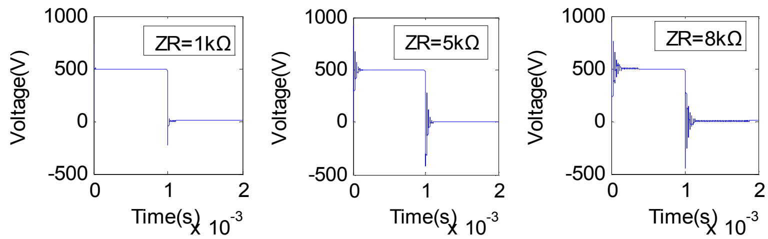

Fig. 7: The simulation results of different food motor characteristic impendence

- R_C = 0.02 Ω/km, L_C = 1 mH/km, C_C = 10 nF/km; Take l = 0.1, 0.5 and 3 km, respectively. The simulation results are shown in Fig. 4.
- R_C = 0.02 Ω/km, l = 0.5 km, C_C = 10 nF/km; Take L_C = 1, 10 and 60 mH/km, respectively. The simulation results are shown in Fig. 5.
- R_C = 0.02 Ω/km, l = 0.5 km, L_C = 1 mH/km; Take C_C = 5, 10 and 40 nF/km, respectively. The simulation results are shown in Fig. 6.

It can be concluded from Fig. 4 to 6 that when the switch frequency is same, overvoltage at food motor end increases with the increase of cable length, cable capacitance and decreases with the increase of cable inductance. Oscillation cycle and oscillation duration of overvoltage at food motor end increases with the increases of cable parameters (length, inductance and capacitance).

The influence of characteristic impendence of food motor on line-to-line voltage at food motor end: The values of cable parameters are as follows: R_C = 0.02 Ω/km, L_C = 1 mH/km, C_C = 10 nF/km, l = 0.5 km; And the rise/fall time t_r/t_f is 1 usec; Take the characteristic impedance Z_R of food motor to 1, 5 and 8 kΩ, respectively. The simulation results are shown in Fig. 7.

It can be concluded from Fig. 7 that when the switch frequency is same, overvoltage at food motor end increases with the increase of characteristic impedance of motor. Oscillation cycle has nothing to do with food motor characteristic impedance, whereas the oscillation duration increases with the increase of characteristic impedance of motor.

RESULTS AND DISCUSSION

BP (Back Propagation) neural network is a forward multi-layer neural network based on the BP algorithm and its topology is a layered forward network which is composed of input layer, hidden layer and output layer. The completeness theorem of BP neural network mapping ability shows that a three-layer network can approximate any continuous function with arbitrary precision (Zhang *et al*., 2012). Therefore, this study tries to use neural network to determine the weight of every influence factor by making system identification for overvoltage influence factors, memorizing past experience to the network structure, establishing the neural network model and then implementing forward knowledge reason by the trained neural network. Because the BP neural network contents are not the focus of this study, this study only briefly gives the build steps of BP neural network weight model.

Design the structure: Design the structure (input layer, hidden layer and output layer) of calculating the influence factor weights.

Non-dimensionalization of the influence factors: To eliminate the different dimension of the influence factors, dimensionless processing for the influence factor values is done based on Eq. (5). And the dimensionless matrix $X = (x_{ij})_{n\times m}$ can be got:

$$x_{ij} = \frac{x'_{ij} - \min_{i=1}^{n} x'_{ij}}{\max_{i=1}^{n} x'_{ij} - \min_{i=1}^{n} x'_{ij}}, i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \quad (5)$$

Calculate the output layer: Ctivation function f (x) used to calculate the output layer in this study is the common single-polarity Sigmoid function, which can be expressed as $f(x) = \frac{1}{1+e^{-x}}$.

Weight calculation: After all the samples' trining is finished and the network accuracy is also achieved, a weight matrix V (the connection weight matrix from input layer to hidden layer multiplies by the connection weight matrix from hidden layer to output layer) can be got. The weights of m-factors can be got by calculating the absolute sum of matrix V and then normalization. The specific formula can be expressed as:

$$w_j = \frac{\sum_{l=1}^{k} |v_{jl}|}{\sum_{i=1}^{m} \sum_{l=1}^{k} |v_{jl}|}, j = 1, 2, \cdots, m \quad (6)$$

The values of parameters affecting overvoltage at food motor end are displayed in Table 1, while other parameters coincide to part 2.2. Set the number of input

Table 1: The value of parameters that affect overvoltage at food motor end

Inductance (mH)	Capacitance (pF)	Length (km)	Rise/fall time (usec)	Food motor resistance (kΩ)	Voltage (V)
1	10	0.50	1	5	919
1	10	0.50	2	5	888
1	10	0.50	3	5	814
1	10	0.50	5	5	654
1	10	0.50	10	5	583
1	10	0.50	20	5	539
1	10	0.50	30	5	518
1	10	0.05	1	5	583
1	10	0.10	1	5	654
1	10	0.20	1	5	848
1	10	1.00	1	5	929
1	10	1.50	1	5	931
1	10	2.00	1	5	932
1	10	3.00	1	5	932
2	10	0.50	1	5	901
5	10	0.50	1	5	861
10	10	0.50	1	5	817
20	10	0.50	1	5	762
40	10	0.50	1	5	697
60	10	0.50	1	5	656
80	10	0.50	1	5	627
1	1	0.50	1	5	723
1	5	0.50	1	5	882
1	8	0.50	1	5	908
1	15	0.50	1	5	934
1	20	0.50	1	5	943
1	30	0.50	1	5	953
1	40	0.50	1	5	959
1	10	0.50	1	0.5	599
1	10	0.50	1	1	733
1	10	0.50	1	2	838
1	10	0.50	1	3	880
1	10	0.50	1	8	941
1	10	0.50	1	10	949

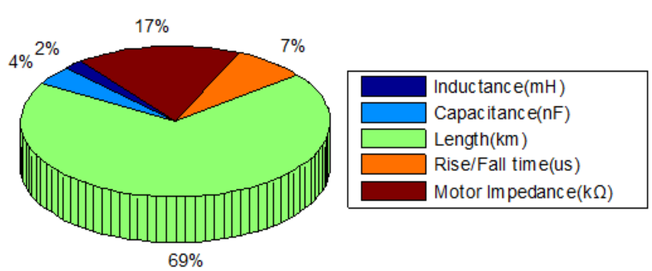

Fig. 8: The weight diagram of influence factors

layer nodes to 5, the number of hidden layer nodes to 11 and the number of output layer nodes to 1; set the learning rate to 0.02 and the error rate to less than 10^{-5}. The weights of influence factors are analyzed by the BP neural network.

In Fig. 8, it can be concluded that the cable length is the main factor that cause overvoltage at food motor end, followed by the characteristic impedance of food motor and the rise/fall time of voltage pulse. Thus it can be confirmed that in the process of inverter system design, to suppress overvoltage at food motor end, shorten the cable length between the inverter and food motor is the first choice; Secondly, induction food motor with smaller characteristic impedance can be chosen based on actual working frequency, thus can avoid mismatch between food motor and cable; And then to some extent, take measures to prolong the rise/fall time of the PWM voltage pulse; Lastly, a cable with appropriate electrical parameters can be selected.

CONCLUSION

In this study, systematic analysis and simulation have been done for the factors that affect overvoltage at food motor end in PWM inverter fed induction food motor system. It can be consistently concluded that the rise/fall time of PWM voltage pulse, the nondestructive cable parameters (length, inductance and capacitance) and the characteristic impedance of food motor are the factors affecting overvoltage at food motor end. Cable parameters also affect oscillation cycle and oscillation duration of overvoltage at food motor end, while rise/fall time and food motor impedance have nothing to do with oscillation cycle, which also affect oscillation duration.

By weight analysis it can be confirmed that cable length is the most important factor affecting overvoltage at food motor end, followed by characteristic impedance of food motor and the rise/fall time of voltage pulse, cable inductance and capacitance have the minimal impact. In this study, the research content of overvoltage at food motor end has certain guiding significances for the analysis and design of PWM inverter system.

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