CONTROL OF DC MOTOR EXTERNAL RESISTOR STARTER BY USING ARMATURE CURRENT DECAY SENSING TECHNIQUE

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ABSTRACT
Advancement of AC motor over last 100 years coupled with regular maintenance requirement of a DC motor has made DC motor become unpopular to be widely used in modern industries. Even so, for industries that require high torque output and variable speed, DC motor is still in demand. Nonetheless, reducing high starting current is a challenge. This paper discusses control strategies for reducing high starting current to a considerable safer value, i.e. at least 3 times of full load torque. In doing so, a set of external resistance is applied to the armature winding of DC motor and equipped with the automatic control switch. The value of carried load torque determines the execution of control switch, thus resulted in reduction of start-up period with minimum losses and improves the efficiency of forward-reverse control. The results suggested that no ill effect on speed smoothness and torque load carrying capacity during starting time.

Keywords: DC motor, armature current decay sensing, resistor starter, peak ratio protocol, unequal peak ratio, equal peak ratio.

INTRODUCTION
Increasing of fuel costs in global market has impacted the electric bill directly. This situation has creating awareness towards saving and energy efficiency. Electrical loads such as motors, air-conditioner and heater are major contributor to the energy demand. In case of electric motor, heavy industry such as mining and steel production has applied DC motor for heavy duty operation with variety-speed requirements. The forward-reverse control requires the on-off action frequently that led to the waste of energy if the start time is too long. Therefore, the focus of energy saving demands continuous research to reduce the start-up time without neglect the advantages offered by the DC motor.

A DC motor has the advantage of high load-carrying capacity. This advantage compared to AC 3-ph induction motor is because the input voltage is fed directly to the stator and rotor. Power is supplied to the rotor through the carbon brush and commutator, where high currents and bad commutation effects can cause a reduction of life expectancy to the brush and commutator [1].

Usually if the full-load motor is switched on, the starting current will shoot up to more than 4 times the full load current [2]. Since the armature current is directly proportional to the developed torque. Therefore, the high starting torque should be tamed to fit the current value, which is usually up to 2 times the full load [2–5]. The reduction of starting current can be by up to 2.5 to 3 times in order to optimize the load-carrying capacity of the motor [6, 7].

The shunt-connected DC motor is selected because of its ability to maintain nearly uniform speed while carrying different loads. This contrasts with the series connection of a DC motor that provides a significant speed drop when there is an addition or reduction of load. With the ability of this motor, research for applications requiring smooth speed such as hoisting control could be devoted to the torque control [8].

The method of inserting external resistance in series with the internal resistance of the armature has been applied since the 1940s [2, 3]. This method is still relevant compared to the soft starter using electronic switching, such as a DC/DC and AC/DC controller, if factors such as the low-cost equipment, uncomplicated control system and low maintenance costs are to be considered. The studies conducted nowadays focus more on improving the time control method for reducing the resistance effectively [6, 9], where the rate of settling time can be reduced to minimize power loss in the resistors. In this study, the method of sensing the armature current decay (ACDS) to the valley value could reduce the settling time at a better rate for the range of carried loads.

EXPERIMENT DETAILS
DC motor control can be done only by controlling the rate of the armature current and voltage terminals. Field current (I_f) will be set fixed, even though it has a great effect on the slope of the graph of speed vs. torque. This is due to the safety factor, in which case the field circuit is an open circuit and will cause the motor to accelerate dramatically. There are several criteria that should be good for a starter:

i. Consistent acceleration
ii. No impact of speed "bumping"
iii. Starting current does not exceed 3 times the rated current
iv. Short settling time.

The maximum load-carrying capacity

An additional feature for a good starter is the ability to rearrange operations based on changes in the load. It also has the ability to control minimum E_a at the starting point, which is at least 50% of the rated value.
Figure-1 shows the developed DC motor control system. The main unit in the system is starter unit, controller unit and selector unit.

**External resistance calculation**

Figure-2 shows the starter unit of DC motor control system. The starter consists of a set of resistors with the closing mechanism. Mechanically, a closure on each resistor is activated when receiving signal '1' from the controller, where holding contact will ensure that it remains closed although the signal has changed to '0'. The contact will only open when the input voltage to the armature terminal is in the off state. The value of a set resistor depends on the following steps:

i. The maximum armature current required, $I_{A\text{max}}$.
ii. The back emf, $E_a$ when the armature current reaches the valley state.
iii. The peak value for each closure. (peak ratio protocol, PRP)
iv. The number of steps depends on ii and iii.

**Figure-2.** 3-point starter of DC motor control system

Unlike the soft-starter that applies a pulse width modulation signal (PWM), the resistor values are fixed, so the values of the full load parameters are taken to determine the value of a set resistor. The two methods of calculation used are unequal peak ratio (UPR) [1] and equal peak ratio (EPR) [4]. Table-1 shows the 5 Hp DC motor manufacturer data.

**Table-1.** 5 Hp DC motor parameters.

<table>
<thead>
<tr>
<th>$V_a$ (V)</th>
<th>$R_a$ (Ω)</th>
<th>$I_{fl}$ (A)</th>
<th>$T_{e\text{fl}}$ (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>240</td>
<td>2.581</td>
<td>21.18</td>
<td>20.36</td>
</tr>
</tbody>
</table>

**Unequal Peak Ratio (UPR) method**

The voltage equation at the armature side:

$$V_a = E_a + I_a R_a$$  \hspace{1cm} (1)

The required maximum armature current is N times the full-load current. The peak value for each closure. (peak ratio protocol, PRP) is set not equal to each other.

$$I_{A\text{max}} = NI_{fl}$$  \hspace{1cm} (2)

At the starting point the motor is at standstill, $E_{fl} = 0V$.

$$V_a = 0 + PRP_1 I_a (R_1 + R_2)$$
$$R_T = R_1 + R_2 + R_3$$  \hspace{1cm} (3)

A moment later, the current begins to decay to the valley value, and at the same time the back emf, $E_a$ begins to rise:

$$E_{fl} = V_a - I_{fl}*(R_7+R_8)$$  \hspace{1cm} (4)

Closure of resistor $R_1$ occurs and the current value climbs to the top value and by setting of $PRP_1$: 

$Pr_4$:
\[ R_2 + R_3 = \left[ \left( V_a - E_a \right) / \left( PRP_1 \cdot I_{at} \right) \right] - R_a \] (5)

and again, the current begins to decay to the valley value, and at the same time the back emf, \( E_a \) begins to rise:

\[ E_a = V_a - I_{at} \cdot R \] (6)

Closure of resistor \( R_1 \) occurs and the current value climbs to the top value and by setting of \( PRP_2 \):

\[ R_3 = \left[ \left( V_a - E_a \right) / \left( PRP_2 \cdot I_{at} \right) \right] - R_a \] (7)

**Table-2.** (a) Value of \( I_{max} \) and \( E_a \) for the PRP setting (b) a calculated external resistance.

<table>
<thead>
<tr>
<th>PRP (_{0,1,2})</th>
<th>( I_{max} ) (A)</th>
<th>( E_a ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>42.36</td>
<td>120</td>
</tr>
<tr>
<td>1.6</td>
<td>33.89</td>
<td>165</td>
</tr>
<tr>
<td>1.2</td>
<td>25.42</td>
<td>185</td>
</tr>
</tbody>
</table>

**Table-3.** A calculated external resistance for the EPR method (given \( R_T = 3.085 \) Ω).

<table>
<thead>
<tr>
<th>( R_1 ) (Ω)</th>
<th>( R_2 ) (Ω)</th>
<th>( R_3 ) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.125</td>
<td>0.590</td>
<td>0.370</td>
</tr>
</tbody>
</table>

**Equal Peak Ratio (EPR) method**

The value of external resistances can be found by applying the equations as stated below, where the total value of resistance depend on the maximum current to be reduced.

**Finding resistance ratio,**

\[ \lambda = \frac{R_T}{1 + \lambda \cdot \lambda^2} \] (8)

Where, \( R_3 = \frac{R_T}{1 + \lambda \cdot \lambda^2} \) (9)

\[ R_2 = \lambda R_3 \] (10)

\[ R_1 = \lambda^2 R_3 \] (11)

**Controller Subsystem**

The armature current decay rate of a DC motor is depend on the ratio of the time constant \( T = L_a/R_a \) in the following equation of the armature current:

\[ I_a (t) = \left( V_a - E_a (t) \right) e^{-t/T_a} \] (12)

Reduction of the total resistance value occurs when the armature current reaches the valley point. The controller works by comparing the current developed torque value (which armature current is the key component) to the actual load torque that has been carried, as stated in the following equation:

\[ \tau_{Load} \geq KI_{at(valley)} - J \frac{d\omega(t)}{dt} - B\omega(t) - \tau_f \] (13)

It is found that when the armature current reaches the valley point, the speed is constant (zero acceleration). Thus the setting of the \( J \frac{d\omega(t)}{dt} \) is set to be 0. The comparator equation becomes:

\[ \tau_{Load} \geq KI_{at(valley)} - B\omega(t) - \tau_f \] (14)

The equation (14) then can be converted to the block diagram as shown in Figure-2.

**Figure-3.** Controller circuit of DC motor control system.

**Figure-4.** Controlling the starter subsystem.
Through this method, the system does not require a pre-determined value because the operation is based on the actual value. The load torque, motor speed and current values is read continuously through the torque, speed and current sensors that are installed on the motor. The controller automatically gives the reading '1' if $E_a$ has reached the end point.

**SIMULATION RESULTS**

The result is compared between UPR and EPR method. The result indicator is based on the settling time, motor speed, armature current and armature voltage.

Figure-6 shows the simulation results using the unequal peak ratio. The motor reaches steady state when $t_{sFL}=1.17s$ for full load and when $t_{sML}=1.16s$ for maximum load. The incremental value of speed and the armature voltage on the point of resistance reduction are shown in Table-4.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>N (Rpm)</th>
<th>$E_a$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$= 0.56</td>
<td>124.7</td>
<td>127.9</td>
</tr>
<tr>
<td>$t_2$= 0.86</td>
<td>165.3</td>
<td>167</td>
</tr>
<tr>
<td>$t_3$= 1.04</td>
<td>178.5</td>
<td>176.3</td>
</tr>
<tr>
<td>$t_4$= 1.17</td>
<td>184.3</td>
<td>182.3</td>
</tr>
</tbody>
</table>

(b) At max -load, 27 Nm

Table-5. Motor speed and armature voltage at full load and maximum load using the equal peak ratio.

(a) At full load, 20.36 Nm

(b) At max load, 32 Nm

Figure-7 shows the simulation results using the equal peak ratio. The motor reaches steady state when $t_{sFL}=1.29s$ for full load and when $t_{sML}=1.25s$ for maximum load. The incremental value of speed and the armature voltage on the point of resistance reduction are shown in Table-5.
Table-5. Motor speed and armature voltage at full load and maximum load using the equal peak ratio.

(a) At full load, 20.36 Nm

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>N (Rpm)</th>
<th>$E_a$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$ = 0.54</td>
<td>118.6</td>
<td>119.9</td>
</tr>
<tr>
<td>$t_2$ = 0.87</td>
<td>144.7</td>
<td>146.3</td>
</tr>
<tr>
<td>$t_3$ = 1.1</td>
<td>162.3</td>
<td>179.4</td>
</tr>
<tr>
<td>$t_4$ = 1.29</td>
<td>182.4</td>
<td>184.4</td>
</tr>
</tbody>
</table>

(b) At max load, 32 Nm

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>N (Rpm)</th>
<th>$E_a$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$ = 0.47</td>
<td>59.13</td>
<td>60.31</td>
</tr>
<tr>
<td>$t_2$ = 0.82</td>
<td>96.09</td>
<td>96.28</td>
</tr>
<tr>
<td>$t_3$ = 1.15</td>
<td>146</td>
<td>145.4</td>
</tr>
<tr>
<td>$t_4$ = 1.25</td>
<td>152.5</td>
<td>154</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The smooth acceleration with a constant increase of $E_a$ is obtained by using the equal peak ratio method. However, for the full load the total time to reach the steady state is shorter for the unequal peak ratio method, which is 1.17 s compared with 1.29 s for the equal peak ratio method. The number of steps affects the time to achieve a settling time. More steps give a smooth speed rate, but will require a longer settling time.

There are no speeds bumping impact for both of these methods since the reduction of external resistance occurs as the current reaches the current valley. This effect can be controlled by the availability of an efficient controller.

Both methods used are able to limit the current not more than 3 times the full load current. However, the equal peak ratio method is better at carrying the load torque compared to the unequal peak ratio method, with a difference of 7 Nm.

These methods can provide 50% of the $E_a$ value at the starting point for the maximum load but not for the full load. This is because the input voltage is fixed and does not have the flexibility to reduce external resistance.

For further study, the armature current decay detection methods (ACDS) can be applied to the soft-starter that employed solid state devices. Voltage control will be more efficient if a lower starting voltage can be fed to the motor and then armature voltage can be increased consistently with the proposed controller. The expectations for a shorter starting time and the capability to carry a higher load can be achieved by using the efficient controller to control the pulse width modulation (PWM) signal.

REFERENCES


APPENDICES

Appendix-A. Nomenclature

$DC$ Direct current  
$AC$ Alternate current  
$T_{dev}$ Developed torque  
$K$ Field constant  
$\rho_a$ Armature current  
$I_r$ Field current  
$R_a$ Armature internal resistance  
$t_s$ Setting time  
$ACDS$ Armature current decay sensing  
$V_a$ Armature terminal voltage  
$E_{emf}$ Back emf voltage in armature  
PWM Pulse width modulation  
$PRP$ Peak ratio protocol  
$UPR$ Unequal peak ratio  
$EPR$ Equal peak ratio  
$J$ Inertia of the motor  
$B$ Viscous friction constant  
$\phi$ Rotational speed  
$\lambda$ Resistor ratio  
$\tau$ Coulomb friction torque
Appendix-B. Motor data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical power, $P_m$</td>
<td>5 HP or 3.7 kW</td>
</tr>
<tr>
<td>Terminal voltage, $V_T$</td>
<td>240 Vdc</td>
</tr>
<tr>
<td>Field voltage, $V_F$</td>
<td>360 Vdc</td>
</tr>
<tr>
<td>Rated speed, $N_0$</td>
<td>1750 rpm/183.3 rad/s</td>
</tr>
<tr>
<td>Armature resistance, $R_A$</td>
<td>2.581 Ω</td>
</tr>
<tr>
<td>Armature inductance, $L_A$</td>
<td>0.028 H</td>
</tr>
<tr>
<td>Field resistance, $R_F$</td>
<td>281.3 Ω</td>
</tr>
<tr>
<td>Field inductance, $L_F$</td>
<td>156 H</td>
</tr>
<tr>
<td>Field-armature mutual inductance, $L_{AF}$</td>
<td>0.9483 H</td>
</tr>
<tr>
<td>Total inertia, $J$</td>
<td>0.02215 kgm²</td>
</tr>
<tr>
<td>Viscous friction coefficient, $B_m$</td>
<td>0.00253 Nms</td>
</tr>
<tr>
<td>Coulomb friction torque, $T_f$</td>
<td>0.5161 Nm</td>
</tr>
</tbody>
</table>