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ANALYSIS AND SIMULATION STUDIES FOR THE ESTIMATION OF ROTOR POSITION IN SENSORLESS BLDC

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Abstract - Initial rotor position information is essential for brushless dc motor in order to ensure its stable operation. A simple method for determining the initial rotor position of a sensor less brushless dc motor at standstill is discussed in the paper. The principle behind the rotor position estimation is based on simple detection and comparison of phase voltages and dc link current responses thus relating it with stator inductances. The advantage of this method of estimation of rotor position is that it requires only three voltage pulse injection, and a resolution of 30^o is achieved. Moreover no other parameters of the machine are required. The effectiveness of the method is validated by simulation results in Matlab Simulink platform.

Keywords*-Brushless DC (BLDC), saturation, rotor position, voltage pulse injection.*

I. INTRODUCTION

. Brushless DC motors (BLDC), because of their high starting torque, high efficiency, no excitation losses, silent operation and durability is now being widely used in number of industrial applications such as compressor, in electrical vehicles, hard disc drives and in medical applications.

An inverter driven three-phase BLDC motor, as shown in Fig.1, requires the rotor position information in order to ensure a stable operation. Usually the position information is available using position sensors like Hall Effect sensors or position encoders, which increases the cost of overall system that makes the system unfavourable. Hence the concept of sensorless system is being implemented which is highly reliable and particularly for numerous low cost applications.

One of the major problems faced by sensorless BLDC is the initial start-up, since most of the sensorless techniques are based on back-EMF voltage detection which disappears at standstill. To solve this start-up problem an open-loop start-up is described in [2]. The major drawback of this method is that any temporary reverse rotation due to unknown load characteristics can result in no rotor position information. Another solution to this problem is to align the rotor to predefined position by exiting any two phases of the motor for a predefined set time [3]. This pre-alignment of rotor can fail due to large static friction. Hence it is very necessary to solve all the start-up problems and to estimate the initial rotor position of the rotor in order to have a smooth stable sensorless operation for BLDC motors.

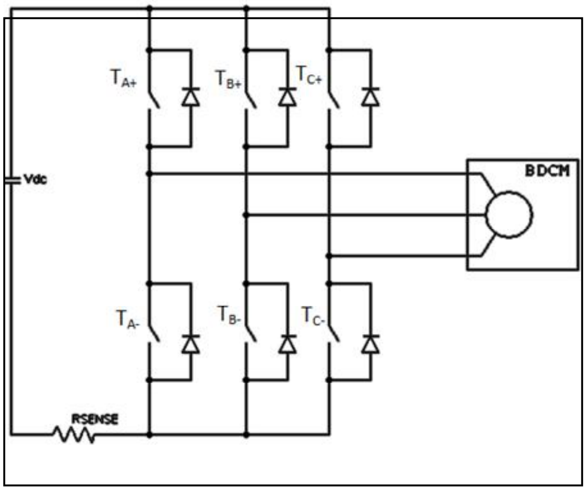


Fig.1 Inverter driven three phase BLDC Motor

Rotor position estimations based on inductance variation methods are usually done for BLDC that has iron core stator. In [4] rotor position estimation is done by ratio of differences of current responses that is obtained from applying voltage pulses. But this method proves to be inapplicable for low cost applications as it requires three current sensors for each phase.

In this method, rotor position estimation is based on simple detection and comparison of phase voltages and dc link current responses, resulting from the injection of three voltage pulses to the selected windings [1].

II. INITIAL ROTOR POSITION ESTIMATION TECHNIQUE

The principle behind the rotor position estimation is the saturation effect of the stator core, caused by the rotor magnet as described in [4]. Fig.2 shows the measured current response and equivalent inductance versus rotor position in a BLDC motor.

The rotor position estimation comprises of two methods.

1. Inductance comparison process
2. Polarity determination process

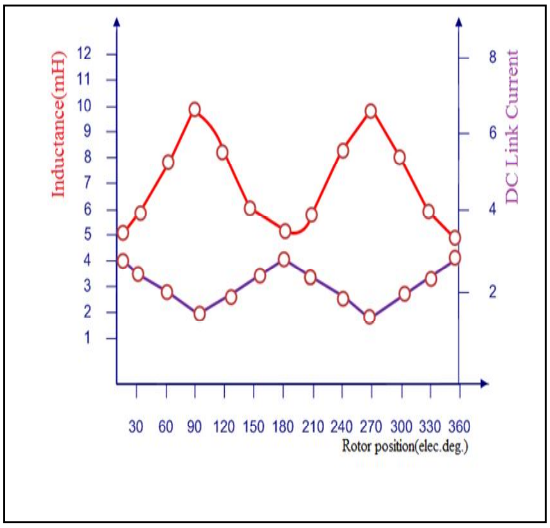


Fig.2 Current response and equivalent inductance versus rotor position of a BLDC machine (phase-A)

A . Inductance Comparison Process

The process comprises of a sequence of voltage pulses applied to selected pair of windings. Voltage pulse injection consists of two intervals: pulse injecting interval and freewheeling interval. Fig.3 shows the pulse injecting interval along with a freewheeling interval of a BLDC motor after the first voltage pulse injection. The entire process can be explained as follows.

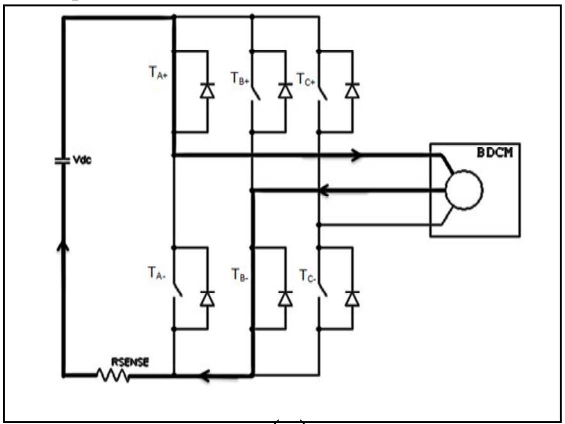
(1) First Voltage Pulse Injection:The first voltage pulse is injected to the phase-A and phase-B turning on switches T_{A+} and T_{B-}. Fig.3(a) shows the pulse injecting interval and Fig.3(b) shows freewheeling interval, while the phase voltage can be measured across the floating phase-C with respect to the negative dc bus. Taking winding resistance and the current sensing resistance negligibly small, the dc bus voltage can be approximated as

$$\left.\begin{aligned} V_{dc} &\approx [L_A(\theta_0)+L_B(\theta_0)]\frac{di_{1(on)}}{dt} \\ &\approx L_A(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}}+L_B(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}} \\ &= V_{AN1(on)}+V_{NB1(on)} \end{aligned}\right\} \quad (1)$$

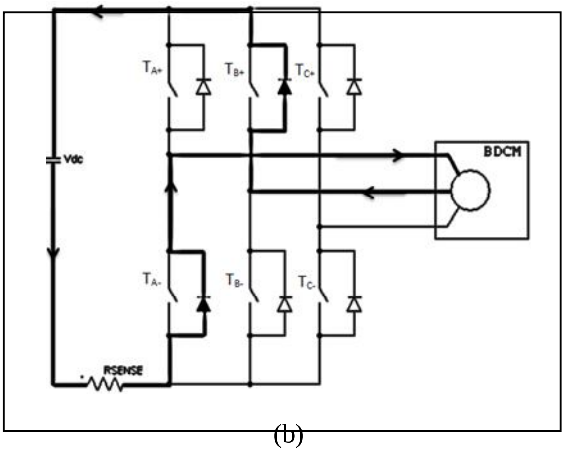
where

$$\begin{aligned} L_A(\theta_0) &= L_{aa}(\theta_0)+L_{ab}(\theta_0) \\ L_B(\theta_0) &= L_{bb}(\theta_0)+L_{ba}(\theta_0) \end{aligned} \quad (2)$$

Here L_{aa} and L_{bb} are effective self inductances of phase-A and phase-B respectively. Likewise L_{ab} and L_{ba} are the mutual inductances due to currents in phase-B and phase-A. θ_0 is the initial rotor position, $\Delta i_{1(on)}$ is the current change during turn on time and $T_{s1(on)}$ is the turn on time interval.$V_{AN1(on)}$ and $V_{NB1(on)}$ are phase voltages during the pulse injecting interval. The magnitudes of mutual inductances L_{ab} and L_{ba} have same value and therefore the induced phase voltages arise mainly from self inductances of phase-A and phase-B.



(a)



(b)

Fig.3. Switching states of BLDC motor during injection of first voltage pulse. (a). Pulse-injecting interval (b). Freewheeling interval

From (1), $V_{AN1(on)}$ and $V_{NB1(on)}$ can be written in terms of V_{dc} as

$$\left.\begin{aligned} V_{AN1(on)} &= \frac{L_A}{L_A+L_B}.V_{dc} \\ V_{NB1(on)} &= \frac{L_B}{L_A+L_B}.V_{dc} \end{aligned}\right\} \quad (3)$$

After the initial voltage pulse injecting interval, switches T_{A+} and T_{B-} are turned off. Consequently the freewheeling interval occurs as shown in Fig.4(a).The DC bus voltage during freewheeling interval can be written as

$$\begin{aligned} V_{dc} &\approx -L_A(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}}-L_B(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}} \\ &= V_{NA1(off)}+V_{BN1(off)} \end{aligned} \quad (4)$$

Where $\Delta i_{1(off)}$ is the change in current during freewheeling interval, $T_{s1(off)}$.$V_{NA1(off)}$ and $V_{NB1(off)}$ are the voltage across phase-A and phase-B respectively during freewheeling interval. These voltages can be measured across phase-C with reference to -V_{dc}.

The total voltage drop across phase-A and phase-B during the pulse injecting interval is opposite to freewheeling interval, respective change in bus voltage will reflect on the phase-A and phase-B windings. Therefore from (1) and (4) it can realized that

$$\left.\begin{aligned} &L_A(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}} = -L_A(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}} \text{ or} \\ &V_{AN1(on)} = V_{NA1(off)} \\ &L_B(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}} = L_B(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}} \end{aligned}\right\} \text{ or}$$

$$V_{NB1(on)} = V_{BN1(off)} \qquad (5)$$

Also phase–A and phase-B voltages during freewheeling interval can be written as

$$\left.\begin{aligned} V_{NA1(off)} &= \frac{L_A}{L_A + L_B}V_{dc} \\ V_{BN1(off)} &= \frac{L_B}{L_A + L_B}V_{dc} \end{aligned}\right\} \qquad (6)$$

From (3) and (6)

$$V_{NA1(off)} - V_{BN1(on)} = \frac{(L_A - L_B)}{(L_A + L_B)}V_{dc} \qquad (7)$$

Hence from (7) it is very clear that values of L_A and L_B can be compared to each other by voltage comparison between $V_{NA1(off)}$ and $V_{BN1(on)}$, since both of them are referred to $-V_{dc}$.

(2) Second Voltage Pulse Injection: In the same way the second voltage pulse is injected to switches T_{A+} and T_{C-} of the phase-A and phase-C for the same time interval. During the pulse injecting interval phase-A is connected to $+V_{dc}$ and phase-C is connected to $-V_{dc}$. phase-B will be the floating phase, across which the phase voltages can be measured. Similar to first voltage pulse injection during freewheeling interval switches T_{A+} and T_{C-} are turned off. Hence L_A and L_C can be compared by comparing $V_{NA2(off)}$ and $V_{NC2(on)}$.Therefore it can be written as

$$V_{NA2(off)} - V_{NC2(on)} = \frac{(L_A - L_C)}{(L_A + L_C)}V_{dc} \qquad (8)$$

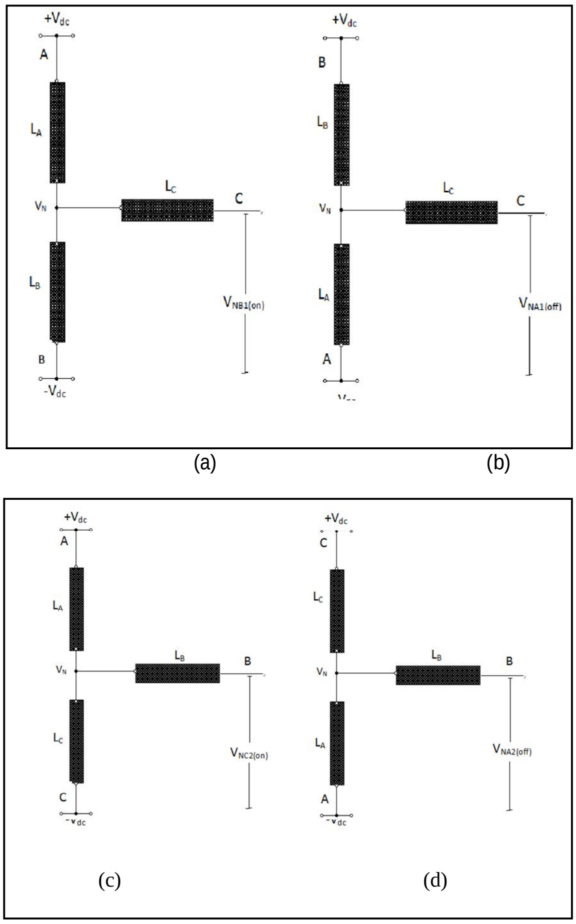


Fig.4.Terminal voltage detection. (a) Pulse injecting interval of first voltage pulse injection. (b) Freewheeling interval of first voltage pulse injection. (c) Pulse injecting interval of second voltage pulse injection (d) Freewheeling interval of second voltage pulse injection.

Where $V_{NC2(on)}$ is voltage across phase-C during pulse injecting interval and $V_{NA2(off)}$ is the phase-A voltage during freewheeling interval. These voltages can be measured across phase-B with reference to -V_{dc}.. In the same way the relative values of L_B and L_C can be obtained from $V_{BN1(on)}$ and $V_{NC2(on)}$ as

$$V_{NB(on)} - V_{NC(on)} = (L_B - L_C)\frac{L_A}{(L_A + L_C)(L_A + L_B)}V_{dc} \qquad (9)$$

Hence the winding inductances L_A, L_B and L_C can be compared to each other using (7) and (9). Table.1 gives information on relationship between inductance comparisons and possible initial position of the rotor (the north pole). So in order to determine the polarity of rotor magnet an additional third voltage pulse is required.

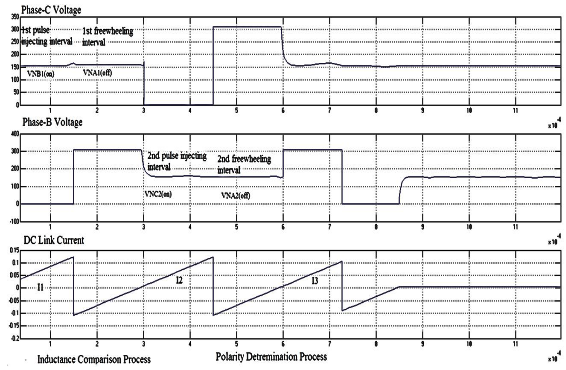


Fig.5 Actual phase voltage and DC link current for both the processes

TABLE 1
Determination of initial rotor position for BLDC

Phase Voltage Comparison	Inductance Comparison	Possible Initial Position	3rd Injection	Peak Current	Initial Rotor Position
$V_{NB1} > V_{NA1}$ $V_{NC2} \geq V_{NA2}$ $V_{NB1} > V_{NC2}$	$L_B > L_C \geq L_A$	$0^\circ < \theta^\circ < 30^\circ$ $180^\circ < \theta^\circ < 210^\circ$	T_{C+}, T_{A-}	$I_2 > I_3$ $I_3 > I_2$	$0^\circ < \theta^\circ < 30^\circ$ $180^\circ < \theta^\circ < 210^\circ$
$V_{NB1} \geq V_{NA1}$ $V_{NC2} < V_{NA2}$ $V_{NB1} > V_{NC2}$	$L_B \geq L_A > L_C$	$30^\circ < \theta^\circ < 60^\circ$ $210^\circ < \theta^\circ < 240^\circ$	T_{C+}, T_{A-}	$I_2 > I_3$ $I_3 > I_2$	$30^\circ < \theta^\circ < 60^\circ$ $210^\circ < \theta^\circ < 240^\circ$
$V_{NB1} < V_{NA1}$ $V_{NC2} < V_{NA2}$ $V_{NB1} \geq V_{NC2}$	$L_A > L_B \geq L_C$	$60^\circ < \theta^\circ < 90^\circ$ $240^\circ < \theta^\circ < 270^\circ$	T_{C+}, T_{A-}	$I_2 > I_3$ $I_3 > I_2$	$60^\circ < \theta^\circ < 90^\circ$ $240^\circ < \theta^\circ < 270^\circ$
$V_{NB1} < V_{NA1}$ $V_{NC2} \leq V_{NA2}$ $V_{NB1} < V_{NC2}$	$L_A \geq L_C > L_B$	$90^\circ < \theta^\circ < 120^\circ$ $270^\circ < \theta^\circ < 300^\circ$	T_{B+}, T_{A-}	$I_3 > I_1$ $I_1 > I_3$	$90^\circ < \theta^\circ < 120^\circ$ $270^\circ < \theta^\circ < 300^\circ$
$V_{NB1} \leq V_{NA1}$ $V_{NC2} > V_{NA2}$ $V_{NB1} < V_{NC2}$	$L_C > L_A \geq L_B$	$120^\circ < \theta^\circ < 150^\circ$ $300^\circ < \theta^\circ < 330^\circ$	T_{B+}, T_{A-}	$I_3 > I_1$ $I_1 > I_3$	$120^\circ < \theta^\circ < 150^\circ$ $300^\circ < \theta^\circ < 330^\circ$
$V_{NB1} > V_{NA1}$ $V_{NC2} > V_{NA2}$ $V_{NB1} \leq V_{NC2}$	$L_C \geq L_B > L_A$	$150^\circ < \theta^\circ < 180^\circ$ $330^\circ < \theta^\circ < 360^\circ$	T_{B+}, T_{A-}	$I_3 > I_1$ $I_1 > I_3$	$150^\circ < \theta^\circ < 180^\circ$ $330^\circ < \theta^\circ < 360^\circ$

B. Polarity Determination Process

In polarity determination process polarity of rotor current is determined by injecting an additional third voltage pulse to a selected pair of switches, As an example, for the condition $L_A>L_B\geq L_C$, the possible initial rotor positions can be either at $60^o < \theta_0 < 90^o$ or at, $240^o < \theta_0 < 270^o$. So in order to determine where the rotor magnet pole is actually located, a third voltage pulse is required to be injected The peak dc current should be noted at the end of all the three voltage pulse injecting intervals across the resistor R_{SENSE}.

The principle behind the determination of polarity of rotor magnet is clearly described in [2] that, the winding currents from the injected pulse voltages can either increase or decrease stator saturation which may result in the variation of stator inductance, as shown in Fig.2. Therefore the third voltage pulse is injected according to the following conditions.

1) If the possible initial position of the rotor is between 0^o - 90^o or 180^o - 270^o, turn on switches T_{C+} and T_{A-} and compare I_2 with I_3 .
2) If the possible initial position of the rotor is between 90^o - 180^o or 270^o - 360^o, turn on switches T_{B+} and T_{A-} and compare I_1 with I_3.

Thus by comparing the DC link currents the initial rotor position of BLDC motor can be estimated from the Table1.

III. SIMULATION RESULTS

Effectiveness of the method is validated from simulation results. Simulation was done in MATLAB Simulink platform. Fig.6 shows the simulation circuit for the estimation of rotor position of BLDC. The parameters of the motor used for simulation is given in Table.2. Voltages pulses are given to the respective inverter switches using separate signal builders for 150µs duration. The DC bus voltage is 310V. The phase voltage during the pulse injecting period is measured across the input terminals of the BLDC motor with reference to $-V_{dc}$

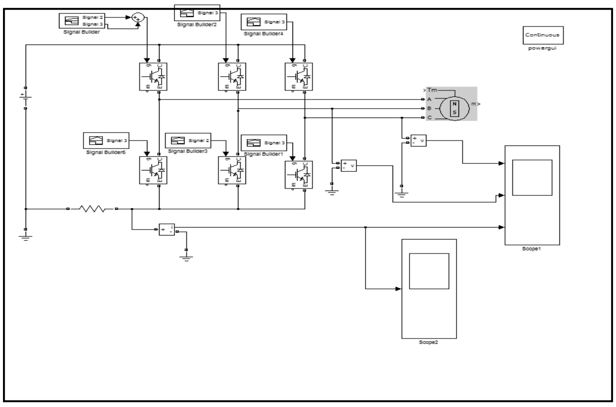


Fig.6 Simulation set up for estimation of rotor position in BLDC

TABLE
Machine Parameters

ZNo.of poles	4
DC bus voltage	310V
Stator phase inductance	0.2H
Stator phase resistance	2.8Ω

The current responses during all three pulse injecting period is measured across resistor R_{SENSE}, value of which is very negligible. So the voltage drop across this resistor is not taken into account.

The phase voltages and current responses are measured at the middle of the entire three pulse injecting interval, ie at 75µs to avoid the adverse effects due to parasitic elements. The validity of this method is verified by conducting the simulation for $\theta=31^o$ by adjusting the motor model. Switching signals to inverter switches are shown in Fig.7. Initially pulse signals are given to the switches T_{A+} and T_{B-} for 150µs.After the first pulse injection voltage across phase-C is measured with reference to

$-V_{dc}$, which is found to be $V_{NB1} \geq V_{NA1,}$ as shown in Fig.8.

Second pulse injection is given in such a way to turn on switches T_{A+} and T_{C-}. Then the voltage is measured across phase-B with reference to $-V_{dc}$ and is found to be as $V_{NA2}<V_{NC2}$ and $V_{NB1}>V_{NC2}$. From Table1, it is clear that the choice of third pulse injection is to turn on switches T_{C+} and T_{A-} and also the current comparison is between I_2 and I_3. Accordingly the estimated initial rotor position can be between $30^o<\theta_0<60^o$ sector. Fig.9 shows the dc link current that is measured for rotor position $\theta=31^o$. It is very clear from the result currents $I_2 > I_3$.

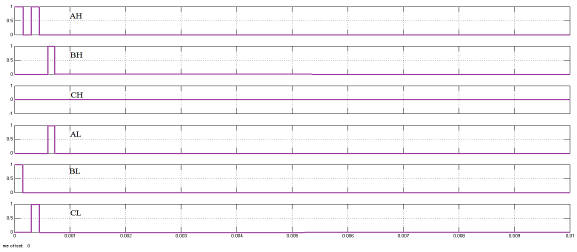


Fig.7. Switching pulses for θ=31°

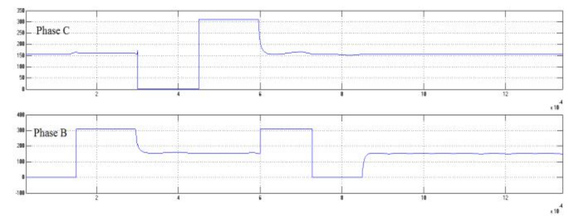


Fig.8 Actual phase voltages for both processes against corresponding gate signals at θ=31°

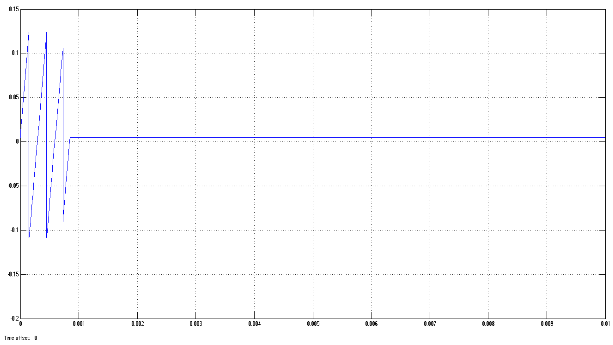


Fig.9. Actual DC link current for both processes against corresponding gate signals at θ=31°

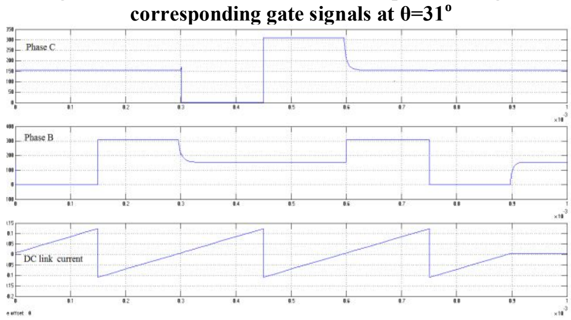


Fig.10. Actual phase voltages and dc link current for both processes against corresponding gate signals at θ=125°

Fig.10 shows the actual phase voltage and dc link current for both processes against corresponding gate signals at $\theta=125^o$. Initially pulse signals are given to the switches T_{A+} and T_{B-} for 150µs. After the first pulse injection voltage across phase-C is measured with reference to $-V_{dc}$, which is found to be $V_{NB1} \leq V_{NA1}$.Second pulse injection is given in such a way to turn on switches T_{A+} and T_{C-}, and then the voltage is measured across phase-B with reference to $-V_{dc}$ and is found to be as $V_{NA2}<V_{NC2}$ and $V_{NB1}<V_{NC2}$. From table1 it is clear the choice of third pulse injection is to turn on switches T_{B+} and T_{A-} and also the current comparison is between I_1 and I_3. Accordingly the estimated rotor position is the $120^o<\theta_0<150^o$ sector. Hence this method for rotor position estimation gives a resolution of 30^o.

IV. CONCLUSION

A simple estimation to determine the initial rotor position of sensorless BLDC has been analyzed in the paper which gives a resolution of 30^o. This paper is based on the theory that the winding inductance is varied due to the influence of saturation of stator core. It requires only three voltage pulses to be injected for the estimation of rotor position. Additionally one sensing resistor is added to a typical sensorless drive. Moreover no machine parameters are required. Hence this method proves to be very effective for the rotor position estimation in position sensorless BLDC. Once the motor has started, any other sensorless algorithms can be implemented reliably to change over the machine to running mode.

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