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# UNIFIED CONTROL STRUCTURE OF MULTI-TYPE INTERIOR PERMANENT MAGNET MOTOR

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## Abstract

This paper presents the control strategy structure to extract the speed torque characteristic for the newly designed three phase Multi Type Interior Permanent Magnet Motor. The proposed structure with the driving circuits exhibit the performance of torque characteristics of the stepper motor and brushless motor with independent coil winding per phase especially used as an in-wheel motor in agricultural applications. Brushless Direct Current motors exhibit characteristics of generating high torque at high speed while the Permanent Magnet Stepper motors has characteristic of generating high torque at low speed. The typical characteristics of the above two are integrated in the proposed structure with a complex control structure that handle the switching complexity and speed control in real time. Thus, a specially designed driving system is essential to drive and control this special motor. The evaluation of the motor mechanical characteristics when applying load torque is also presented. The result determines the practical torque range applicable for each motor configuration and as combined machine.

Keywords: Multi-type Interior permanent magnet motor, Multi-mode drive,
BLDC motor, PMST motor.

## 1.Introduction

The technological advancements in recent years enhance the inventions of efficient machine design that cater to commercial and industrial applications. The proposed machine in this paper is one such that encircles the functionality of the Brushless DC Machine (BLDC) and Permanent Magnet Stepper (PMST) motors,

## Nomenclatures

| | |
|---|---|
| $I_m$ | Motor current, A |
| $T_{BLDC}$ | BLDC motor torque, Nm |
| $T_L$ | Load torque, Nm |
| $T_M$ | Motor torque, Nm |
| $T_{PMST}$ | PMST motor torque, Nm |
| $V_c$ | Chopper voltage, V |
| $V_f$ | Frequency signal, V |
| $V_h$ | Hall voltage, V |
| $V_s$ | Supply voltage, V |

***Greek Symbols***

| | |
|---|---|
| $\alpha$ | Duty cycle |
| $\sigma$ | Rotor half pitch, deg |
| $\tau_m$ | Motor torque, Nm |
| $\tau_s$ | Steady torque, Nm |
| $\omega_m$ | Rotational speed, rpm |
| $\omega_n$ | No load speed, rpm |

**Abbreviations**

| | |
|---|---|
| BLDC | Brushless Direct Current |
| DAQ | Data Acquisition |
| EMF | Electro Motive Force |
| MTIPM | Multi Type Interior Permanent Magnet |
| NI | National Instruments |
| PMST | Permanent Magnet Stepper |
| PWM | Pulse Width Modulation |

hence is named as Multi-type Interior Permanent Magnet Motor (MTIPM). As a high torque performance motor this motor has a promising feature as in-wheel motor for agriculture application such as tractors or for other industrial machinery. MTIPM can be used widely for applications including speed or positioning applications. In order to derive the operational control structure of this novel machine a thorough investigation of the individual operating characteristics of the BLDC and PMST is an ideal approach and later integrating to understand the performance as combined functionality. PMST precisely controls the motor position without any feedback mechanism. With its open-loop configurations they are known to be susceptible to resonances at a step rate equal to the frequency of resonance [1]. This type of motor can precisely control commutation sequences without any feedback mechanism. The stator excitation of PMST can be generated using a frequency controller module instead of a rotor position sensor [2-5]. They are widely used in numerous position control application and in constant low speed applications such as robotics, printers, process control systems and many more applications [3-5]. Nonetheless, PMST are more suitable for low speed application due to its limited operating speed ranges [2, 3]. On high load inertia, this motor unlikely can perform in micro-stepping and create an overshoot response to repeated step [3].

On the other hand BLDC motors are used increasingly for wide range applications due to their high power-torque and high efficiency capability. BLDC operates in full torque mode at a variable bi-directional high speed as the speed is proportional to the applied voltage [6]. Essentially BLDC machines require a feedback sensor such as Hall sensor to detect the rotor position to generate the switching sequences from the controller making it to operate in the closed loop configuration. Three Hall sensors are placed on the three-phase BLDC to generate a six-state commutation control signal. This output signal from the Hall sensor determines the actual rotor position to derive the triggering sequence [6-10]. The logic circuit then decodes the signal to continuously control the motor rotation. The proposed machine has a rotor with a buried magnet on the interior and a wound field stator, which is connected to a power electronic switching circuit. Rotor position information is required for the power electronics driver when it operates as a BLDC machine. To integrate the above functionality the machine structure encompasses three hall sensors as feedback element. MTIPM is usually driven with sinusoidal currents or rectangular current for both configurations. The driving control system of the MTIPM is constructed based on the motor structure that can operate in two different motor configurations. The combination of both made the MTIPM motor has a wider operating torque region which can be used in a variety of applications including speed or positioning applications. The comparison of BLDC motor and PMST motor is shown in Table 1.

**Table 1. Motor characteristics.**

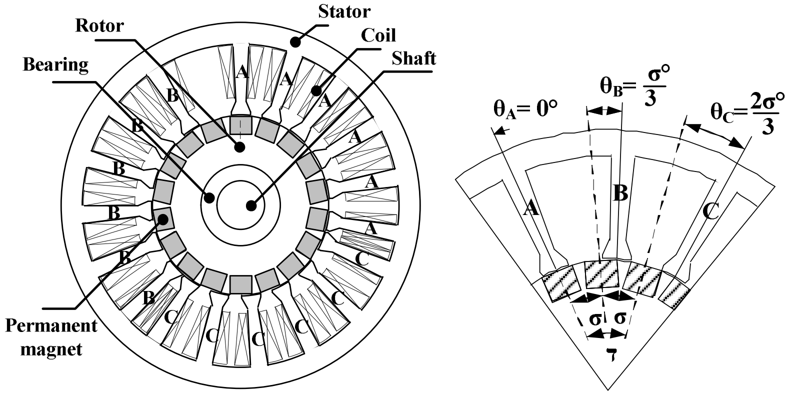
| | **BLDC** | **PMST** |
|---|---|---|
| **Torque** | High speed | Low speed |
| **Speed torque curve** | Linear curve | Extended curve |
| **Control structure** | Close-loop | Open-Loop |
| **Speed control** | Voltage supply | Pulse frequency |
| **Feedback** | Necessary | Unnecessary |
| **Vibration** | Less vibration | Higher vibration |

## 2. Structural Characteristics

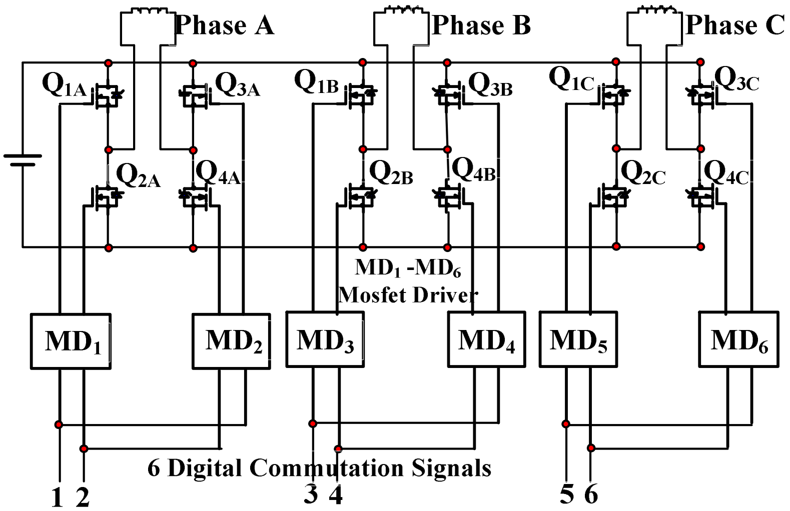
### 2.1. Motor structure

As an Interior Permanent Magnet (IPM) structure the rotor is embedded with permanent magnets in back to back arrangement for the electromagnetic field reaction toward the coil slot in the stator for the motor energisation [11]. The machine is designed for three phase operation with the stator enclosing eighteen independent coils with the equal number of magnets in the rotor. The MTIPM proposed is designed and fabricated based on the design procedure as in [11-13]. Figure 1(a) shows the basic structural configuration of the designed motor. The motor stator and rotor arrangement are made offset to each other. The independent coil winding allows the phase energisation more compact. Furthermore, this configuration allows the manipulation of different phase energisation, one, two or three phase per turn on switching to achieve a variety of a desired torque.

The basic principle lies in the positioning of its stator teeth with the pitch arrangement of the motor. Figure 1(b) shows the positioning of the teeth arrangement. The position of the stator teeth is arranged based on the pitch angle ($\tau$) at the rotor which consists of rotor slot and a permanent magnet. In order to arrange the stator teeth for three phase MTIPM, the teeth of Phase A is positioned at 0º, the Phase B and Phase C at $(1/3)^{rd}$ and $(2/3)^{rd}$ of the rotor half pitch (σ) respectively. The movement of the motor is the magnetic interaction between the rotor and stator. The mechanical rotation is feasible as the rotor rotates due to the interaction of two magnetic fields caused by the permanent magnets mounted on the rotating rotor and the magnetic field in stationary windings of the stator coil. In order to create the magnetic polarity of the stator, the direction of the injection current in winding coils is determined based on the polarity at rotor slot. Figure 1(c) shows the independent coil placing of the MTIPM motor. The information on the rotor and stator position, the pitch arrangement and the design is crucial in the control structure logic.



**(a) Structural configuration.** **(b) Phase positioning.**



**(c) Coil arrangement.**

**Fig. 1. Structural configuration and coil phasing.**

## 2.2. Speed-torque requirements

A speed torque characteristic of a particular machine is important as it describes the operating mechanical characteristics of the machine. It shows the behaviour of the machine as it tries to match the load requirements with machine characteristics. Figure 2 shows the typical motor drive supplying a load, with the speed-torque curves for both shown. The motor with the drive configuration is coupled mechanically to the load. At any instant the variations of the load is trying to get matched with that of the motor characteristics. In other words towards stability operation the characteristics fall well within the operating conditions. To make the machine more effective operating conditions with the proposed machine the operating characteristics of two different machines with different characteristics are combined to sustain higher stability and improved operational efficiency with the proper control strategy.

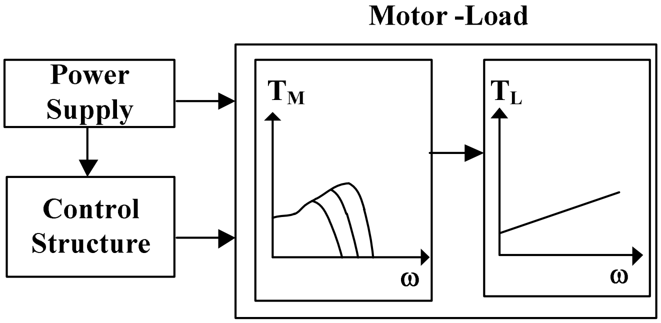


**Fig. 2. Speed-torque requirements.**

To achieve the stability the following equation is to be sustained.

$$\left[\frac{dT_L}{d\omega_m} - \frac{dT_M}{d\omega_m}\right] > 0 \tag{1}$$

Figure 3 shows the sketch of the torque versus speed characteristic of both PMST and BLDC speed torque characteristics. The typical mechanical characteristics of the PMST motor, shows an extended curve pattern. The operating torque for this motor is the greatest at a low speed, which decreases at the high speed application. At certain high speed range, this motor tends to misstep [13]. BLDC motor has a constant operating torque for a speed up to the rated speed. Further than that, the torque starts dropping. BLDC motors exhibit characteristics of generating high torque at high speed while the PMST has characteristic of generating high torque at low speed. And this concept is used in the control structure of the machine. To get the idea of the MTIPM motor operating torque, a laboratory evaluation for each configuration is carried out. Compare to PMST motor, BLDC motor has better performance in the high speed range. For the BLDC machine as can be seen the torque is inversely proportional to the speed of the output shaft. In other words, there is a trade-off between the motor torques delivered at the rate at which the output shaft spins. Motor characteristics are frequently given as two points on this graph. The stall torque ($\tau_s$) represents the point on the graph at which the torque is a maximum, but the shaft is not rotating. The no load speed ($\omega_n$) is the maximum output speed of the motor (when no torque is applied to the output shaft). PMST are all about stall/holding torque, not about RPM. However the BLDC motor provides a fixed preset torque at a range of RPMs. The equations for the torque or angular velocity are given as:

$$\tau_m = (\tau_s - \omega_m \tau_s)/\omega_n \tag{2}$$

$$\omega_m = (\tau_s - \tau_m \omega_n)/\tau_s \tag{3}$$

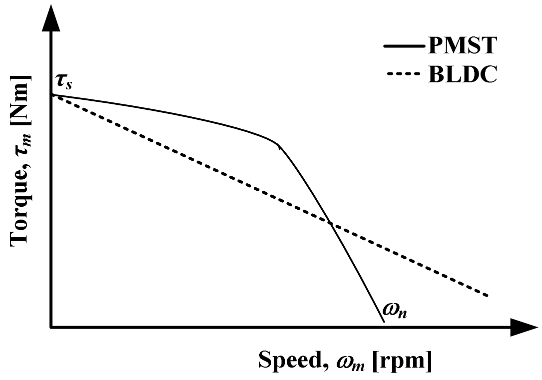


**Fig. 3. Speed-torque characteristics of PMST and BLDC.**

## 2.3. Control structure strategy

Figure 4 shows the control strategy flowchart logic based on the theoretical operation of two different motor configurations with the same pattern of commutation sequence. But, the rotor feedback device using a Hall-effect sensor is essential for the BLDC motor configuration as its commutation is a closed loop control system. Three Hall-effect sensors are placed on a three-phase motor to generate a six-state commutation control signal. The motor configuration is determined by a set of commutation sequence signal to either run in BLDC or PMST motor configuration. In order to use the motor in either configuration, there is a need to stop the motor and change the driver from BLDC to PMST motor configuration and vice versa.

Therefore it necessitates a switching controller between the drivers of the two motors. For instance, PMST motor well known for its performance in low speed meanwhile BLDC motor is best applied for high speed application. Therefore, for a certain condition, a certain configuration mode is operative. For instance to start up with letting the motor be operated in PMST configuration. As the motor runs, the Hall sensor continuously picks the feedback signals and it determines whether it needs to switch to the other motor or run in the same motor configuration depending on the preset speed range. When there is change of mode, it sends a control signal to the switching interface circuit to switch to BLDC driver. Since BLDC driver is a closed loop system, it reads the Hall sensor signal and identify the current phase and speed to cope with the current speed. When the system needs to change the operation from BLDC to PMST configuration, the correct switching steps need to be determined so that the motor rotate smoothly and continuously till the final rotating position. To accomplish this the DAQ module checks current phase and frequency of the Hall sensor signal output and send a signal to the PMST driver for the correct switching step to be executed. Since MTIPM motor has a special coil arrangement, each motor phase is controlled independently. Therefore, the BLDC and PMST motor driver are constructed based on this special requirement. Each driver circuit generates a set of digital commutation signals. Then, the three phase H-bridge inverter circuit is built to convert the digital signals into the switching voltages to electronically control the commutation of the MTIPM motor per phase.

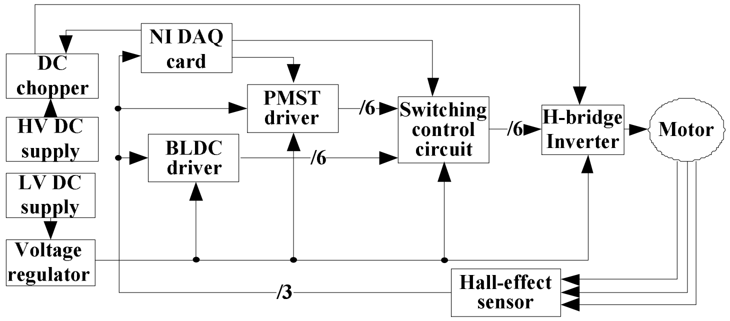
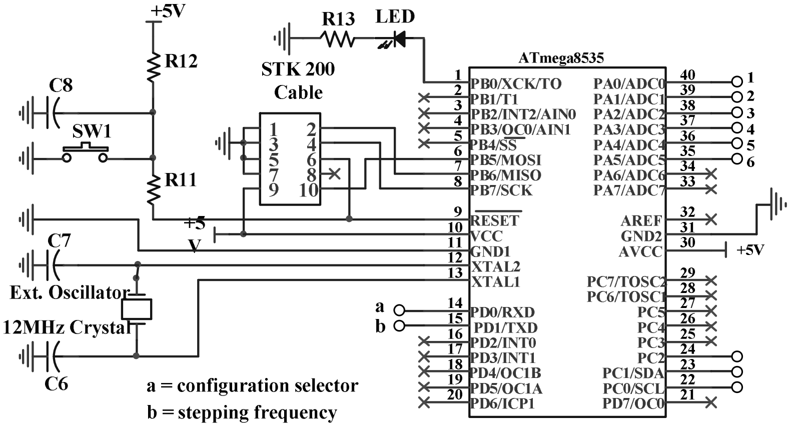


**Fig. 4. Switching logic used for the MTIPM.**

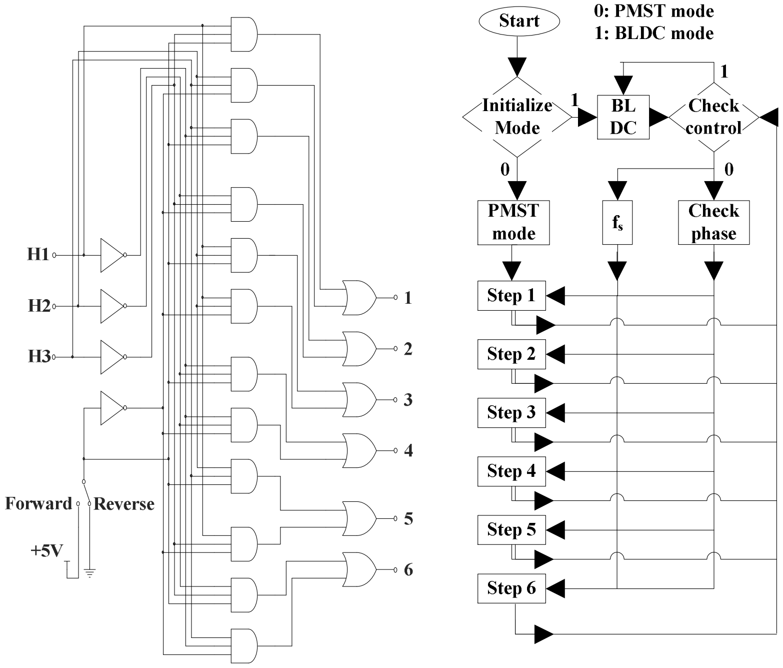
A speed controller is required to control the MTIPM motor in variable speed condition. Since the BLDC motor speed change proportionally to the motor supply, a PWM technique is applied to control the motor acceleration. A chopper circuit is used to vary the voltage by adjusting the duty cycle of the voltage pulses using the injected PWM signal to achieve the desired speed. In BLDC motor configuration, the rotation speed is controlled by voltage as the position of poles on the rotor are detected by the Hall-effect sensor. Commutation logic circuit and switching electronics are used to convert rotor position information to a proper stator phase excitation. The logic circuit is constructed based on logic equations which are derived for each phase from the Hall-effect sensor and back-EMF voltage signal. This circuit sends the triggering signal to the inverter circuit to energise the corresponding phase. On the contrary, PMST motor the speed is controlled by varying the pulse frequency of the rotation sequence in step mode. Therefore, the speed of PMST motor depends on the step frequency which can be controlled by a frequency generator. As the frequency increased, the stepping sequence runs faster and decreased the timing cycle.

Figure 5 shows the block representation of the control strategy used in this design. As can be seen from the circuit configuration the operation of the MTIPM as PMST or BLDC depends on the instantaneous value of the hall sensor as a feedback element. A DC chopper to regulate the voltage is used that control the applied voltage to the motor through the H bridge inverter circuit. By this way the speed of the machine can be brought out. Hence the speed torque characteristics are highly controllable depending upon the variation in speed due to the load changes. The automatic control interface is done using the Data Acquisition Card from National Instruments (NI-DAQ). The unified control structure derives the command through the DAQ card and depending upon the current value would choose either the PMST or the BLDC logic.

Three hall position sensors are used for tracking the current position and are calibrated in the software control. A microcontroller ATmega 8535 (Fig. 5(a)) is used as a control element for the PMST. The mode of configuration and the stepping frequency is generated than push the PMST to the required position based on the circuit configuration in Fig. 5(d). Figure 5(b) shows the logic output used for operation as BLDC machine. Figure 5(c) shows the mode selector logic for the operation of MTIPM. Figure 5(d) shows the complete unified control logic used for the MTIPM motor.

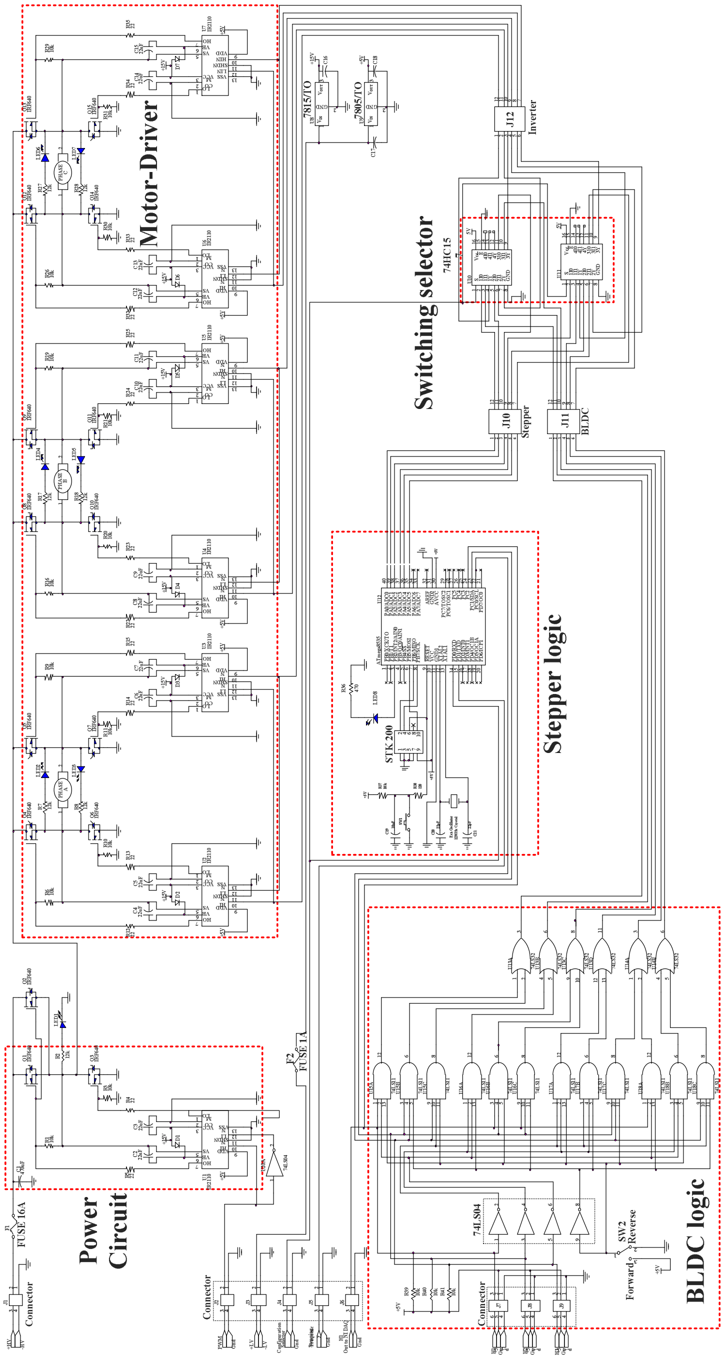


(a) ATMega 8535 control element.



(b) Logic circuit.

(c) Mode selector.



(d) Complete unified control circuit.

**Fig. 5. Control strategy used for the MTIPM.**

## 3. Experimental Investigations

### 3.1. Characteristics as BLDC machine

The speed of the BLDC motor is increased proportionally with the increasing of voltage. Therefore, the torque versus speed characteristic of the BLDC motor is directly obtained from applying a constant increased load and varying the supply voltage. The supply voltage is increased from 20V, 40V and 60V in steps of 10V.

The maximum torque values recorded as 2.8 Nm, 4.6 Nm and 5.5 Nm respectively. The speed torque characteristic of the BLDC motor shows a torque inversely proportional to the motor speed.

$$T_{BLDC}\,\alpha\,\frac{1}{\omega_{\mathrm{m}}} \tag{4}$$

### 3.2. Characteristics as PMST machine

The speed torque characteristic for the PMST motor is slightly different because of the step nature. As the motor speed varied dependent on the stepping pulse frequency supplied, the pulse frequency is controlled to obtain the torque measurement in different speed condition. The pulse frequency is varied from 50Hz to 300Hz by the increment of 10Hz for each 20V, 40V and 60V supply voltage. Under steady state (stall torque condition the torque is constant)

$$\mathrm{T_{PMST}} = \mathrm{K} \tag{5}$$

As the frequency is further increased it follows the pattern as of BLDC motor

$$\mathrm{T_{PMST}}\,\alpha\,\frac{1}{\omega_{\mathrm{m}}} \tag{6}$$

### 3.3. Characteristics as MTIPM motor

From both BLDC and PMST motor torque versus speed characteristic results, it can be concluded that with the increased of voltage, the higher operating torque and wider operating range of the motor performance is achieved respectively. The MTIPM motor torque operating range of both configurations is achieved by combining both PMST and BLDC motor torque versus speed characteristic results. This combination is not experimentally done for the complexity of the evaluation method and the limited facility available. However the control strategy realisation of the MTIPM characteristics as shown in Fig. 6 is realistically possible. In the MTIPM condition the torque region is extended curve and the operating range also increased.

The characteristics resemble the operating conditions at constant speed up to the base speed and after that drooping characteristic of the DC motor. Hence the possibility of control of such type of machine is possible with the design of the controller drive circuit. The characteristics allow the machine to have a wide range of operation condition which is a typical requirement of the variable speed applications. The design and operation of the drive electronics are challenging and an advanced intelligent control would improve the smoothness of the operating conditions with load. This would be reported in our future work through the research disseminations. As can be seen the torque range is extended to the similar operating speed range. The torque equation is given as:

$$\mathrm{T}_{\mathrm{MTIPM}} = [\mathrm{K}_1 \omega_\mathrm{m} + \omega_\mathrm{m} \mathrm{K}_2 / \omega_\mathrm{n}] \tag{7}$$

where $\mathrm{K}_1$ is the motor constant and $\mathrm{K}_2 = \alpha \mathrm{K}_1$ $\alpha$ being the duty cycle

Figures 7(a) and 7(b) shows the frequency variations in the speed, current based on the Hall voltage derived from the feedback signal for the operation mode as BLDC machine. As can be seen as the frequency of the chopping value increases proportionately the speed value also increases. The frequency value is increased due to the decrease in the hall voltage value at a particular position. Under no load condition as is evident from the figure the motor speed is almost constant. The speed range of the frequency variations of 100 Hz to 300 Hz is 112 RPM to 336 RPM. Figures 7(c) and (d) shows the pulsed variations of the speed, current is as expected is oscillating and depending on the time period chopping value the speed of the machine varies. Figure 7(e) shows the combined operation of the PMST and BLDC as a novel MTIPM configuration for the widest range of operating speed.

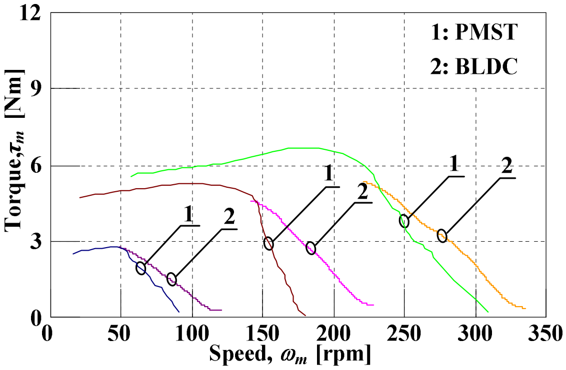
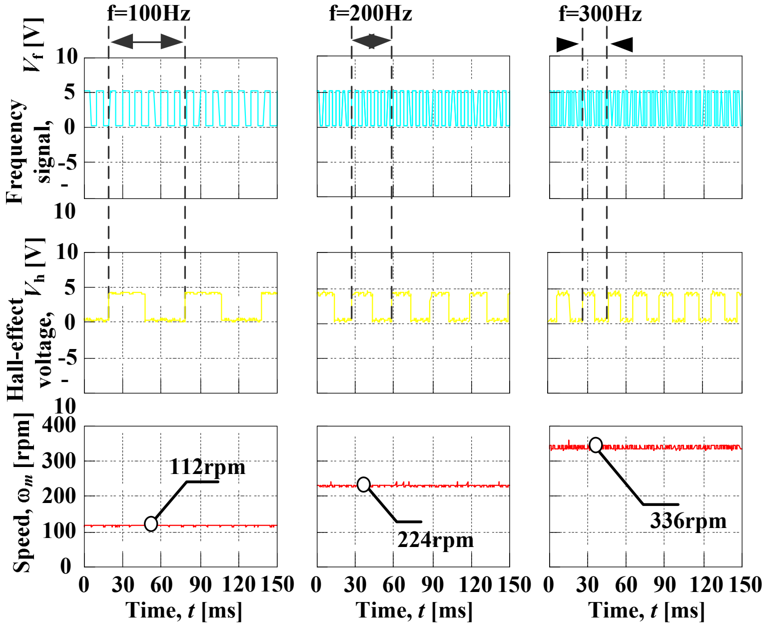


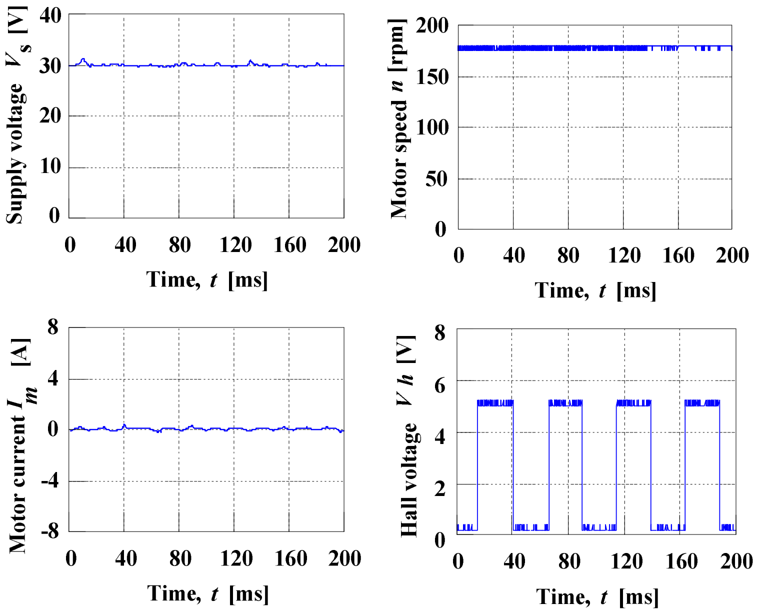
**Fig. 6. Realisation of MTIPM characteristics.**

### 3.4. Effect of load variations

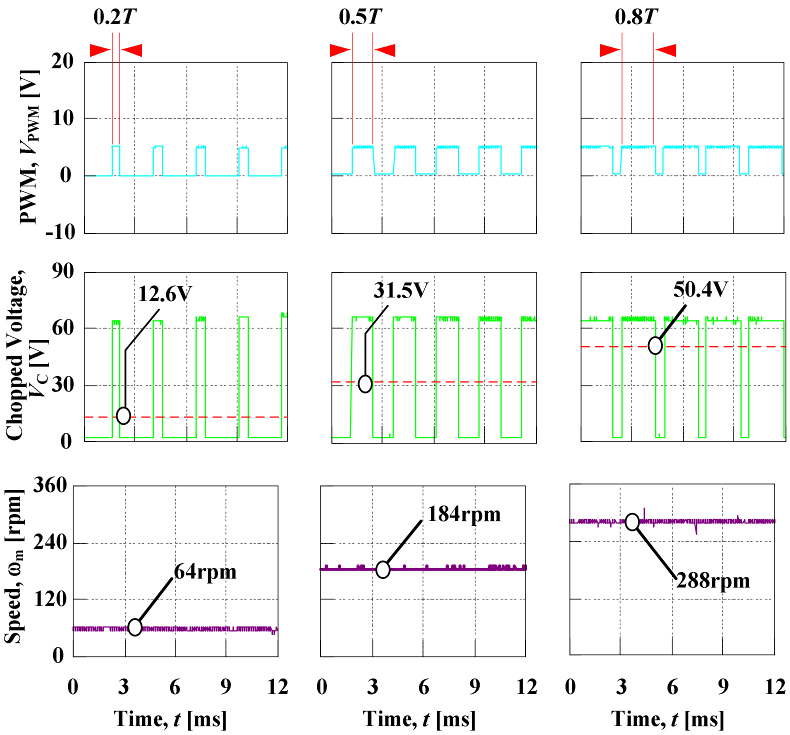
Initially, the Lab view main controller sets the motor to run in BLDC motor manually in high speed condition without load. Then, the mode setting is changed back to the automatic control for the switching to occur. The measurement is taken when the braking force is applied by tightening the screw slowly to simulate a varying load torque. The increasing load is applied to demonstrate its effect on the motor automatic switching mode. As the load torque increased, the speed continues dropping with the increasing torque. When the speed falls below the threshold value, it switches configuration from BLDC to PMST motor smoothly without juddering or misstep. By switching to PMST motor mode, the motor is able to handle the increasing load torque. The configuration switching is indicated by the changes of switching voltage. Figure 8 shows the increasing variable load effect characteristics. The same step applied to evaluate the decreasing of the variable load effect of the MTIPM motor inversely. In contrary of the previous condition, the motor was initiated in PMST motor configuration and the load torque is already applied at the initial condition of this experiment. The load torque is then slowly reduced to evaluate the decreasing load effect on the motor automatic switching mode. The setting of the PWM duty cycle and stepping frequency remained at 95% and 207 Hz respectively.



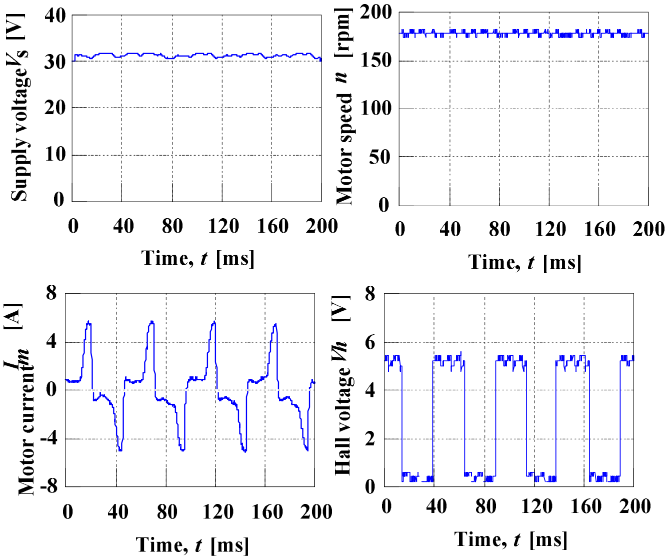
**(a) MTIPM characteristics as BLDC (Frequency and speed).**



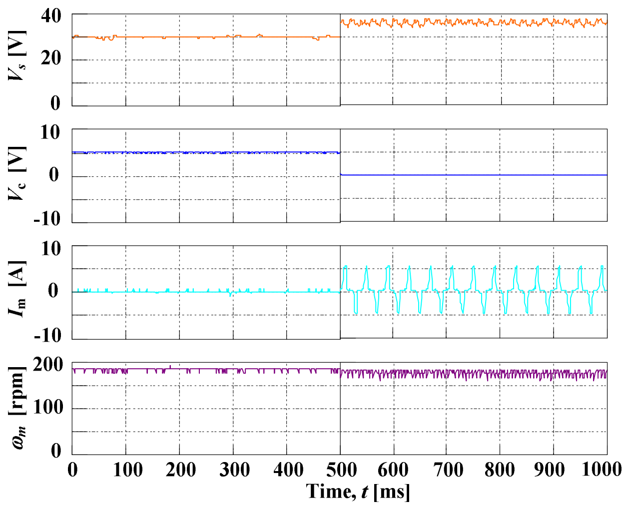
**(b) MTIPM characteristics as BLDC.**



(c) MTIPM characteristics as PMST (Frequency and speed).



(d) MTIPM characteristics as PMST.



MTIPM characteristics over the wide operating speed range.

Fig. 7. Output waveforms for the MITPM configurations.

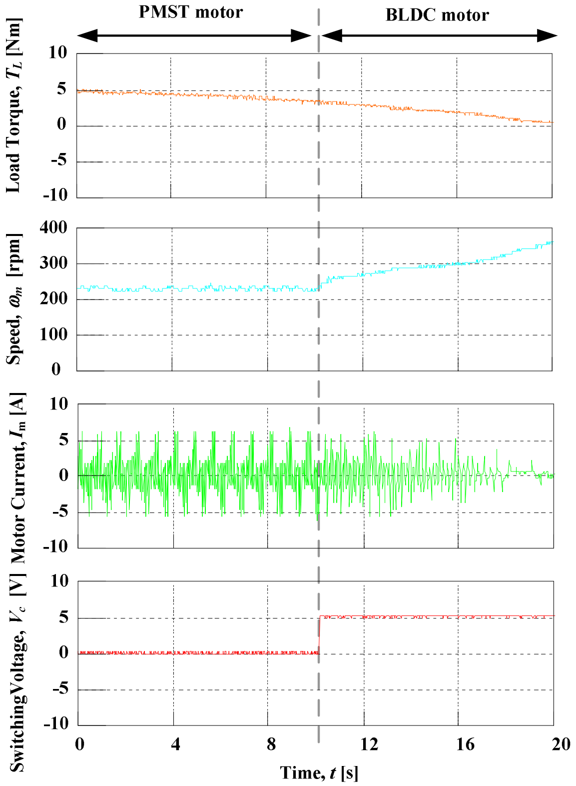


Fig. 8. Increasing load effect investigation.

Figure 9 shows the decreasing variable load effect characteristic. It shows that when the load torque decreased, the speed continues to rise with the decreasing load torque. The configuration is switched from PMST to BLDC motor smoothly when the speed reached the threshold value without misstep and juddering. With the load variations the desired operating characteristics can be realised by the proper logic derived from the control structure. With the simple unified controller the machine can be operated over a wide range of speed with respect to the load requirements.

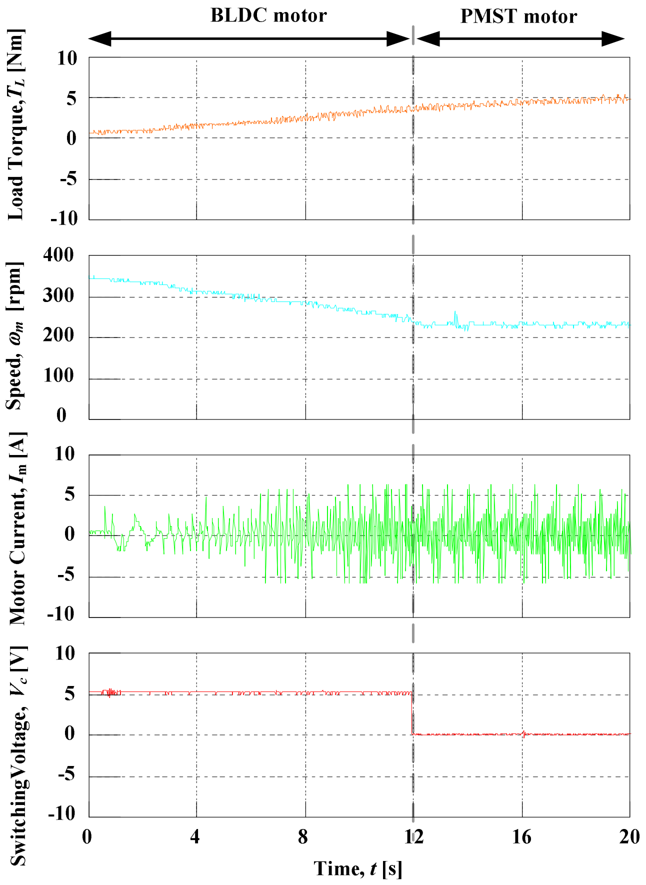
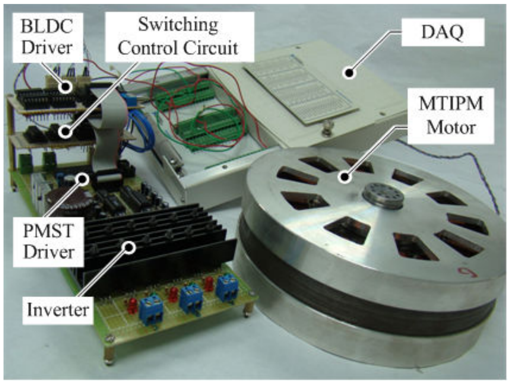
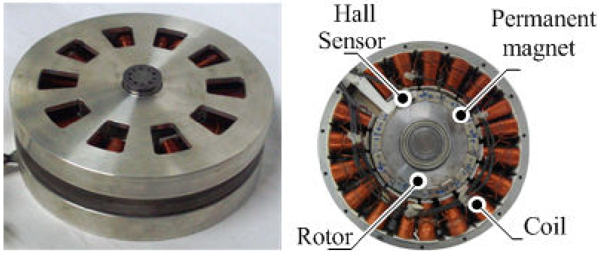


Fig. 9. Decreasing load effect investigation.

Figure 10(a) shows the switching circuits, the driver, the power electronics and the designed motor developed in this investigation with the pertaining applications ad in-wheel motor in agricultural sector. The MTIPM structure with the internal winding configurations as shown in Fig. 10(b) is designed and fabricated and is used as test motor. The comprehensive design procedure of this novel MTIPM including the field analysis is extensively discussed and is well documented in [11-13]. Table 2 shows the parametric dimensions of the developed prototype MTIPM and Table 3 shows the machine ratings.



**(a) Unified switching control with the MTIPM motor.**



**(b) Developed prototype of MTIPM motor.**

**Fig. 10. Prototype of MTIPM motor and its control architecture.**

**Table 2. Parametric dimensions.**

| Part | Element | Value | Units |
|---|---|---|---|
| **Stator** | Outer radius | 100 | mm |
| | Inner radius | 52.5 | mm |
| | Teeth radius | 50.5 | mm |
| | Inner of outer radius | 90 | mm |
| | Slot inner opening | 10/16 | deg |
| | Slot outer opening | 6 | deg |
| **Rotor** | Inner radius | 16 | mm |
| | Outer radius | 50 | mm |
| **Air Gap** | Mechanical Air Gap | 0.5 | mm |
| | Mesh Air Gap Sizing | 0.0008 | mm |
| **Magnet** | Height of magnet | 10 | mm |
| | Width of magnet | 12 | mm |
| | Length of magnet | 30 | mm |
| | Volume of magnet | 3600 | $mm^3$ |
| **Coil** | Wire diameter | 0.8 | mm |
| | Turns per Phase | 640 | turns |
| | Phase resistance | 2.2 | Ω |

Table 3. Ratings of the MTIPM.

| Parameter | Value | Unit |
|---|---|---|
| **Magnetomotive force** | 4750 | Ampere-turns |
| **Maximum power rating** | 600 | Watts |
| **Maximum operating voltage** | 60 | Volts |
| **Maximum operating current** | 10 | Amperes |
| **Coil winding temperature** | 180° - 200° | Celsius |

## 4. Conclusions

The multi configuration switching drive for the MTIPM is presented. The switching drives in real-time for multiple configurations demonstrated in this paper stands apart and open up the designers for the possibility of developing multi configuration motor in the future. This provides a wider speed and operating range of the motor which add contribution in the advancements of electrical machine technology. The results presented suggest that the use of PMST motor configuration in low speed application give a better torque performance than BLDC motor. Meanwhile, the BLDC motor is best applied in high speed application with a higher torque production in that condition. This MTIPM motor applicable for a wider application using the control structure strategy for the driver circuit is yet to be challenged by the existing motors in the market up to the authors' knowledge and hence it opens up a direction towards development and commercialisation of this type of motors in the near future.

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