Closed-Loop Magnetization State Control for a Variable-Flux Memory Machine

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ABSTRACT Variable flux memory machines (VFMM) use magnetization and demagnetization manipulations to adjust machine voltage, achieving wide-speed high-efficiency operation. The machine magnetization state manipulation is a critical concern in the VFMM control. Thus, this article proposes an on-line magnetization state estimation and closed-loop control using the magnetization manipulation signals. The magnetization state manipulation requires voltage injection to create the manipulation current. The current shows non-linear response at different magnetization state because the current changes the magnets state and the machine saturation level. The flux change rate, which is calculated by the injected voltage and the current response, is affected by the non-linearity and utilized in the proposed method for the magnetization state estimation. The proposed magnetization state estimation achieves self-sensing characteristic because the signals in the estimation already exist in the magnetization state manipulation. Based on the estimated and the target magnetization state, the closed-loop magnetization state control is achieved by the voltage injection regulation.

INDEX TERMS Closed-loop magnetization state control, demagnetization, magnetization, magnetization state estimation, motor control, variable-flux memory machine.

I. INTRODUCTION

The permanent magnet synchronous machines (PMSM) have been widely used in the variable-speed applications [1], [2]. Flux-weakening control is required in conventional PMSMs at high speed operations because the rotor back electromotive force (EMF) increases as the speed accelerates and the machine terminal voltage will surpass the DC-link voltage limitation. However, the flux-weakening current leads to additional losses and damages the machine efficiency at high speeds.

Variable flux memory machines (VFMM), also known as memory machines, have been proposed to overcome the flux-weakening current in conventional PMSMs [3], [4]. The key feature of the VFMM is that the magnets used have low coercive-force. The low coercive-force magnets are able to be magnetized or demagnetized with the machine armature current. Therefore, the VFMM has the capability to adjust the back-EMF with the magnetization or the demagnetization current pulses while the machine is still running. When the VFMM accelerates to high speed region, the low coercive-force magnets will be demagnetized so that the back-EMF will reduce and the machine voltage will not violate the voltage limitation. The continuous flux-weakening current and the flux-weakening related losses are eliminated. When the machine speed slows down, the low coercive-force magnets will be magnetized to higher state, gaining more back-EMF. The torque capability increases with the high magnetization state. With the proper arrangement of the magnetization state, the VFMM achieves wide-speed high-efficiency operation.

The VFMM has attracted research interests recently. Numerous papers has studied design and control of the VFMM [5], [6]. The variable-flux feature can be applied to the classic PMSM topologies, e.g., surface-mounted...
VFMM [7], [8] and interior-mounted VFMM [9]–[11]. The magnets can be formed by the combination of low coercive-force magnets and high coercive-force magnets. The hybrid magnets have the topology of series connected and parallel connected types [12]. Moreover, the combination of the series and the parallel connected, i.e., the hybrid-magnetic-circuit type has been proposed [13]. The low coercive-force magnets can be mounted on the stator as the stator permanent magnet VFMM [14], [15]. With the stepwise magnetization control, the constant power speed range can be effectively extended [16]. Variable magnetization pattern PMSMs have been proposed as a special type of VFMM, whose magnets can be partially de/remagnetized. The variable magnetization pattern PMSM can change the harmonic distribution in the air gap flux, thereby reducing torque ripple and losses according to the load condition [17], [18]. Besides the VFMM topologies have been proposed, efforts have been done to increase the performance of the VFMM, e.g., increasing the overall efficiency [19], [20] and reducing the magnetization current [21], [22].

The machine magnetization state (MS) manipulation or the MS control is a critical part of the VFMM control. The magnetization and demagnetization current trajectory design and control are the executing units in the MS manipulation. Basically, the linear magnetization current trajectories has been proposed in [23]. The magnetization current trajectory can be optimized according to the DC-link voltage limitation, thereby increasing the manipulation speed [24]. A straight line stationary frame flux linkage trajectory method has been proposed in [25]. This method uses sinusoidal current trajectories to reduce the required machine voltage. A feed-forward voltage compensation method has been proposed to increase accuracy and response speed of PI-based current controller during the manipulation phases [23]. The dead-beat approach for the manipulation current control has also been proposed with a deep insight to the parameter non-linearity [25].

It is also important to investigate the methods that control the MS to the target MS. A look-up-table can be made to reveal the relation between the applied manipulation current and the MS via analysis or experiments [26]. With the given target MS, the manipulation current amplitude can be derived based on the look-up-table and manipulated by the above mentioned trajectory controller. A more advanced method, i.e., the closed-loop MS control, has been proposed to replace the open-loop look-up-table-based approach [27]. The closed-loop MS control relies on the MS estimation and regulates the manipulation current on-line. The MS estimation becomes critical in the closed-loop MS control because it affects the MS control accuracy directly. Few papers have investigated the MS estimation method for the VFMM. An observer-based method has been proposed in [28] and a neural-network system is embedded in the observer to deal with the parameter non-linearity. The observer-based method uses the machine rotation voltage, however, the back-EMF of low MS at low speed can be extremely small, deteriorating the estimation accuracy. A high frequency signal injection method has been proposed in [29]. This method is based on the non-linear inductance value at different MS and can be applied to zero/low speed.

This article will propose a closed-loop MS manipulation method whose MS estimation uses manipulation signals self-sensing. The regulation of the manipulation current requires voltage injection. The injected voltage can be treated as a flux linkage source that changes the flux linkage and the current. The rate of the flux linkage change to the current change \( d \psi / di \) shows significant relevance to the MS manipulation level, because the MS manipulation changes the PM state and the machine saturation level. The total voltage injection includes the resistance voltage, the induction voltage, and the rotation voltage. However, the flux change is determined by the induction voltage. Therefore, the proposed method separates the induction voltage from the total injected voltage and calculates the flux change \( d \psi \). The flux change rate \( d \psi / di \) is then derived with the current feedback. Based on the finite element analysis result that establishes the relation between \( d \psi / di \) and the MS, the proposed method estimates the MS and regulates the manipulation voltage, achieving the close-loop MS control. The speed information is not required in the MS estimation. Therefore, the proposed method can be applied to very low speed. Besides, the method uses the voltage and current signals that already exist in the manipulation process, so that no additional high frequency signal injection is required. The implementation of the proposed method becomes easy.

II. SPECIFICATIONS OF THE VFMM

A 4-poles and 18-slots spoke-type VFMM has been manufactured and used as the test machine in this study. Fig. 1 presents the cross section (half model), prototype stator and rotor. The rotor shows a spoke type, whose magnets are tangentially magnetized. The low coercive-force magnets, Alnico, are used for the source of the variable flux and flux memory property. The flux barriers in the rotor serve as the guidance for the main flux, making the MS manipulation more easily and reducing the magnetization current amplitude. Specifications of the machine are listed in Tab. 1.

The variable flux property is expressed by the relation between the no-load PM flux linkage and the applied magnetization current. The MS is defined equal to the no-load PM flux linkage, showing the magnetization level of the VFMM. Fig. 2 shows the experimental measured magnetization and demagnetization curves. Ascending \( d \)-axis current pulses were applied, and the no-load back-EMF
TABLE 1. Specifications of the prototype VFMM.

| Parameter      | Value       | Parameter      | Value       |
|----------------|-------------|----------------|-------------|
| Stator outer diameter | 142 mm     | Rated current | 11 A        |
| Stator inner diameter | 75 mm      | Rated torque   | 3.83 Nm     |
| Rotor outer diameter  | 74 mm      | Rated power    | 1.0 kW      |
| PM thickness       | 4.5 mm     | DC voltage     | 270 V       |
| Maximum speed     | 6,000 rpm  | Resistance     | 0.65 Ω      |

was measured. The PM flux was calculated with the back-EMF and the speed settings. The magnetization curve starts to rise when $i_d$ reaches approximately 10 A. The maximum magnetization current is set by 45 A, considering the safe operation of the inverter in this study. The demagnetization curve shows multiple curves that have different starting points on the flux axis. The VFMM was magnetized to several levels, i.e., the points on the flux axis. Then, the negative demagnetization $i_d$ was applied incrementally. The back-EMF was measured, and the PM flux was calculated and plotted. The VFMM can be fully demagnetized to zero flux with $-8$ A demagnetization.

### III. MODEL AND FLUX ANALYSIS OF THE VFMM

#### A. DYNAMIC MATHEMATICAL MODEL FOR VFMM

The VFMM belongs to the category of PM machines. Therefore, the mathematical model of VFMM shows a similar construction to the conventional PM machine model. The difference in the VFMM mathematical model comes from the variable flux property. In the MS manipulation, the $d$-axis pulse current is injected and changes the PM flux linkage. Because the MS manipulation has a short period (usually less than 100 ms), the voltage induced by the change of the flux should be carefully considered in the dynamic mathematical model. The dynamic mathematical model for the VFMM is expressed by (1) and (2):

$$
\begin{align*}
    u_d &= u_{rd} + u_{id} + u_{rfd} \\ 
    &= Ri_d + \frac{d\psi_D}{dt} - \omega \psi_{aq} \\
    u_q &= u_{rq} + u_{iq} + u_{rfq} \\ 
    &= Ri_q + \frac{d\psi_{aq}}{dt} + \omega \psi_D
\end{align*}
$$

where $u_{rd}$ and $u_{rq}$ are the resistance voltages on the $dq$-axis, respectively. $u_{id}$ is the induction voltage on the $d$-axis, expressing by the change rate of the total $d$-axis flux $\psi_D$ (sum of the armature flux and PM flux). $u_{iq}$ is the $q$-axis induction voltage, which is determined by the change rate of the $q$-axis armature flux $\psi_{aq}$. $u_{rfd}$ and $u_{rfq}$ are the rotation voltages on the $dq$-axis, respectively. The rotation voltages are related to the flux amplitude and the machine electrical speed.

#### B. FLUX ANALYSIS IN THE MS MANIPULATION

The manipulation current changes the saturation level of the machine. Therefore, the dynamic model can evaluate the saturation effect because the induction voltage and the rotation voltage are expressed by the function of the flux. The finite element method (FEM) is utilized to derive the flux behavior in the MS manipulations. A method for the flux behavior analysis using the FEM has been proposed in [23]. The manipulation current trajectory is discretized to independent current nodes. Finite element analysis (FEA) is performed with the current value of each node to derive the corresponding $dq$-axis flux and PM flux. The flux of each node forms the flux curve of the analyzed manipulation.

Fig. 3 presents the $d$-axis flux variation in the magnetization and demagnetization manipulations, respectively. The magnetization has the condition of zero initial MS and increasing magnetization $i_d$ from zero to 45 A. The total $d$-axis flux $\psi_D$ in Fig. 3(a) increases as the applied magnetization $i_d$ increases. The slope of $\psi_D$, i.e., $d\psi_D/di_d$, demonstrates the flux change rate related to the magnetization $i_d$. 
The flux change rate appears two major peaks. The first peak locates at approximately $i_d = 0$, where the saturation level of the machine is relatively low. Higher inductance value determines the higher flux change rate. When the current increases, the change rate decreases because of the increasing saturation level. The second peak locates at approximately $i_d = 10$ A. As shown in the magnetization property Fig. 2(a), the PM flux remains almost unchanged until $i_d$ reaches approximately 10 A, following by a sharp increase. The sudden change in the PM flux is the cause of the second peak. After the second peak, $d\psi_D/di_d$ decreases monotonously, because the magnetization speed of the magnets slows down and the overall saturation level increases further.

The cause of the non-magnetization region and the second flux change rate peak can be explained with the BH curves (Fig. 4) of the Alnico magnets used in this article. The working point of the Alnico magnets follows the initial magnetization curve in the direction of the increasing magnetization field strength. In the beginning phase, the slope of the initial magnetization curve is low and the remanence point on the flux density axis remains approximately zero. The magnetization speed of the VFMM is extremely slow in this phase, i.e., the non-magnetization region. In the next phase, the slope of the initial magnetization curve rises sharply, causing the peak value in the flux change rate (i.e., the second peak). The remanence point and the machine MS increase in this phase. The last phase is the saturation phase. The change rate drops down, and the remanence approaches its maximum value. The VFMM is magnetized to its saturated MS.

Fig. 3(b) presents the $d$-axis flux variation and its change rate in the demagnetization. The initial MS is at 0.118 Wb. The demagnetization $i_d$ varies from zero to the full demagnetization current of $-8$ A. Unlike the curves in the magnetization manipulation, $\psi_D$ shows a smooth descending curve. The demagnetization $i_d$ cancels the PM flux and the PM flux decreases because of the demagnetization. Therefore, the saturation level of the machine declines in the demagnetization process. The absolute value of flux slope $d\psi_D/di_d$ (whose actual value is below zero) increases because of the declined saturation level.

IV. CLOSED-LOOP MS CONTROL WITH MANIPULATION VOLTAGE INJECTION

A. RELATION BETWEEN MS AND FLUX CHANGE RATE

The MS manipulation current changes the PM status and the machine saturation level, thereby influencing the machine inductance value during the MS manipulations. The inductance variation reflects the flux change rate in the manipulations as shown in Fig. 3. With the exclusion of the non-magnetization region (the MS will not change until magnetization $i_q$ exceeds 10 A), the flux change rate $d\psi_D/di_d$ shows clear relation to the manipulation current amplitude. The manipulation current then determines the MS. Thus, $d\psi_D/di_d$ can be treated as the benchmark for the MS estimation.

Fig. 5 presents the relation between the machine MS and the flux change rate in the MS manipulations. The two relation curves are derived with the combination of the magnetization and demagnetization curves in Fig. 2 and the flux change rate curves in Fig. 3. On the magnetization side, $d\psi_D/di_d$ decreases as the MS increases because of the increasing saturation level in the magnetization. On the demagnetization side, the flux change rate increases along the direction of MS dropping, which is caused by the reducing saturation level in the demagnetization manipulation. $d\psi_D/di_d$ in Fig. 3 and Fig. 5 is derived from the FEA results and is determined by the machine saturation level. The saturation effect is caused by the applied magnetization or demagnetization current. Therefore, the relation between the MS and the flux change rate is independent of the machine speed and the machine voltage. However, this relation is affected by the $q$-axis current during the MS manipulation period. Because of the cross-saturation effect, the flux change rate and the MS will deviate with different $i_q$, especially when $i_q$ is large (the cross-saturation becomes severe). In order to eliminate this effect, $i_q$ will be controlled zero during the MS manipulation. Therefore, Fig. 5 has the condition of $i_q = 0$.

B. MS ESTIMATION WITH MS MANIPULATION VOLTAGE INJECTION

To create the MS manipulation current, voltage injection on the $d$-axis is required. The injected voltage is treated as a flux
source that changes the $d$-axis flux. Based on Fig. 5, the flux change rate is an indicator of the machine MS. Therefore, the MS manipulation voltage is able to serve in the MS estimation.

Fig. 6(a) presents the proposed estimation system. Two machine operating status variables are estimated in the system, i.e., the MS and the total $d$-axis flux. The MS estimation is used as the feedback in the closed-loop MS control. The $d$-axis flux estimation is used in the current controller to obtain better current control performance.

In the estimation diagram, $u_d(k-1)$ is the $d$-axis voltage at sampling time $k-1$. The voltage is applied to the VFMM between $k-1$ and $k$. The induction voltage $u_{id}$ is the source of the $d$-axis flux change. According to the VFMM model (1), the induction voltage at $k-1$ is calculated by:

$$u_{id}(k-1) = u_d(k-1) - u_{rd}(k) - u_{ref}$$ (3)

The resistance voltage $u_{rd}$ can be calculated with the machine resistance and the average $i_d$ at $k-1$ and $k$, as shown in (4):

$$u_{rd}(k) = R \left[ i_d(k) + i_d(k-1) \right] / 2$$ (4)

The rotation voltage $u_{ref}$, however, requires the $q$-axis flux, which shows high nonlinearity because of the machine saturation during the MS manipulation. Therefore, $i_q$ is controlled to zero temporarily in the MS manipulation, thereby leading to zero $u_{ref}$. The effect of $i_q = 0$ is the absence of the traction torque. Because the MS manipulation has a short period (less than 100 ms), the effect on the mechanical system can be ignored. Therefore, the induction voltage $u_{id}$ and the $d$-axis flux change can be calculated in the difference form as shown in (5) and (6), respectively.

$$u_{id}(k-1) = u_d(k-1) - R \frac{i_d(k-1) + i_d(k)}{2}$$ (5)

$$\Delta \psi_D(k) = \Delta T \cdot u_{id}(k-1)$$ (6)

where $i_d(k)$ and $i_d(k-1)$ are the current at sampling time $k$ and $k-1$, respectively. The induction voltage is separated and derives the flux change. No speed information is required in the calculation of the induction voltage. Therefore, the following MS estimation can be applied at low-speed region. The difference in $i_d$ can be simply calculated with a zero-order hold:

$$\Delta i_d(k) = i_d(k) - i_d(k-1)$$ (7)

Then, the flux change rate $\Delta \psi_D(k)/\Delta i_d(k)$ at sampling time $k$ is calculated. The look-up table whose data is from Fig. 5 uses $\Delta \psi_D(k)/\Delta i_d(k)$ to estimate the magnetization state $MS(k)$ at sampling time $k$. The MS is irreversible in a single MS manipulation. For example, once the machine is magnetized to a certain MS, the MS will not change until the manipulation current reaches the corresponding magnetization current of the present MS nor a new demagnetization is manipulated. Therefore, the estimated MS is latched until new manipulations that can change the MS.

The estimation of the $d$-axis flux uses the first-order linearized integration of $u_{id}$. Therefore, the flux difference $\Delta \psi_D$ is accumulated to the initial MS $MS(0)$, as shown in (8):

$$\psi_D(k) = MS(0) + \sum_{n=1}^{k} \Delta \psi_D(k)$$ (8)
calculation. The estimation for \( \psi_D \) uses the accumulation of \( \Delta \psi_D \), so the error will accumulate. The estimated \( \psi_D \) will be utilized for the calculation of the \( q \)-axis rotation voltage \( \omega \psi_D \). The rotation voltage will serve as the feed-forward voltage in the \( q \)-axis current control. Because \( \psi_D \) varies quickly in the MS manipulation, using voltage feed-forward compensation will increase the response speed of the current controller. The current controller still has the PI regulator, such that the error in the \( \psi_D \) estimation will be compensated by the PI regulator. Besides, the estimated \( \psi_D \) will reset to the MS value after each manipulation. Therefore, the estimation error will not accumulate across different manipulations.

C. CLOSED-LOOP MS CONTROL

Fig. 6(b) presents the diagram of the proposed closed-loop MS controller. The closed-loop MS controller contains three major parts, i.e., the MS estimation, the MS regulator, and the \( dq \)-axis current controller.

The MS estimation records the initial MS and samples \( i_d \) and the \( d \)-axis voltage command \( u_d^* \). \( MS(k) \) and \( \psi_D \) are estimated at each sampling instance based on the algorithm shown in Fig. 6(a). The estimated \( MS(k) \) is transferred to the MS regulator. Based on the target \( MS^* \) and the estimated MS, the MS regulator determines the injection voltage \( u_{mag} \) for the MS manipulation and the working status of the \( d \)-axis current controller.

The algorithm of the MS regulator is shown in Fig. 7. The MS regulator is executed at each control instance. The input variables of the MS regulator are the target \( MS^* \), the initial value \( MS(0) \), and the estimated value \( MS(k) \). If \( MS^* \) is larger than \( MS(0) \), the VFMM will be magnetized in the MS manipulation. The VFMM will be demagnetized when \( MS^* \) is smaller than \( MS(0) \). Once the MS manipulation type is determined, the MS regulator checks the difference between \( MS(k) \) and \( MS^* \). In the magnetization, if \( MS(k) \) is below \( MS^* \), the MS regulator will generate a magnetization voltage \( u_{mag} = U_m^* \) and disconnect the PI regulator of the \( d \)-axis current controller by setting \( k_{pd} = 0 \). The rotation voltage on the \( d \)-axis is zero because \( i_q \) is set by zero. The resistance voltage \( u_{rd} \) is compensated on the \( d \)-axis current controller. Therefore, the magnetization voltage \( u_{mag} \) compensates the induction voltage and creates the change in the \( d \)-axis flux. In the demagnetization manipulations, if the estimated \( MS(k) \) is larger than the target, a negative magnetization voltage \( u_{mag} = -U_m^* \) and the resistance voltage will be injected without the output of the PI regulator, achieving the control effect of demagnetization. \( u_{mag} \) affects the calculation process of the flux change rate, although the relation between the MS and the flux change rate in Fig. 5 is independent of the voltage injected. The configuration of \( u_{mag} \) should consider the balance between the control accuracy and the signal-to-noise ratio. If \( u_{mag} \) is too small, the current change between sampling periods \( \Delta i_d \) will be small. The noises in the current sensors will lead to significant noises in the calculation and estimation. If \( u_{mag} \) is too large, the MS change between sampling periods will be enlarged. The accuracy of the closed-loop MS control will deteriorate.

Because of the irreversible property in a single MS manipulation, once \( MS(k) \) is larger than \( MS^* \) in the magnetization, or is smaller than \( MS^* \) in the demagnetization, the regulator will terminate the MS closed-loop control and set the manipulation voltage \( u_{mag} = 0 \). The \( dq \)-axis currents is then controlled by the PI regulator (with \( k_{pd} = 1 \)) to recover the normal operation (e.g., \( i_d = 0 \) control). The \( q \)-axis current is controlled zero with the PI regulator during the whole MS manipulation. After the MS manipulation, the command \( i_q^* \) is reverted to the value \( f_q^* \) under normal operations. The mathematical expression of the \( dq \)-axis controller is shown in (9) and (10), respectively:

\[
u_{d}^* = k_{pd} \left( i_d^* - i_d \right) + k_{id} \int (i_d^* - i_d)\]
\[u_{mag} = u_{mag} + R i_d \]

(9)

\[
u_{q}^* = k_{pq} \left( i_q^* - i_q \right) + k_{iq} \int (i_q^* - i_q) + \omega \psi_D (k) \]

(10)

where \( k_{pd} \) and \( k_{pq} \) are the proportional gains on the \( dq \)-axis, respectively. \( k_{id} \) and \( k_{iq} \) are the integration gains respectively. \( \omega \psi_D \) in (10) is the instantaneous rotation voltage \( u_{rd} \) on the \( q \)-axis. The \( q \)-axis current controller uses \( u_{rd} \) as the feed-forward voltage compensation, which increases the \( q \)-axis current controller performance in the MS manipulating dynamics.

V. SIMULATION VERIFICATION

The proposed closed-loop MS control was evaluated with numerical simulation. The VFMM was simulated with the linearized formation of the VFMM model (1) and (2). In order to consider the parameter nonlinearity in the MS manipulations, the relation between the current and the flux was derived by the FEA results (e.g., Fig. 3) and was embedded in solving the current by a look-up table. The sampling time for the machine model solving was 1 \( \mu \)s, and the control frequency of the proposed method and the PWM was the same 10 kHz.

Fig. 8 presents the simulation waveform of the magnetization manipulation. The machine initial MS was zero and the target MS was 0.09 Wb. The machine speed was set as 1,800 rpm. In the first stage of the MS manipulation, the MS manipulation voltage \( u_{mag} = 10 \) V was injected. The \( d \)-axis voltage command \( u_d^* \) was formed by \( u_{mag} \) and the resistance voltage \( u_{rd} \). Because of the non-magnetization area of the VFMM, the estimated MS was zero at the early stage of the MS closed-loop control stage. As the magnetization current increased further, the estimated MS began to increase. When the estimated MS reached the target 0.09 Wb, the controller finished the close-loop MS control stage and replaced the \( u_{mag} \) injection by the PI regulator. The MS estimation was also stopped and remained the MS value for the next MS manipulation. In the second stage, \( i_d \) was controlled to the normal operation of \( i_d = 0 \). \( u_d^* \) was formed by \( u_{rd} \) and the output of the PI regulator. \( u_q^* \) was formed by the rotation
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voltage and varied during the whole MS manipulation. $u_d^*$ increased as the $d$-axis flux increased in the first stage. At the end of the MS manipulation, $u_d^*$ dropped to 34 V, which is the back-EMF after the magnetization manipulation. The corresponding PM flux was 0.09 Wb.

Fig. 9 presents the waveform in the demagnetization simulation. The machine speed was 3,000 rpm. The initial MS was 0.12 Wb and the target MS was 0.09 Wb. The control process is similar to the process in the magnetization manipulation. A negative $u_{mag} = -5$ V was injected in the first stage. The estimated MS dropped as $i_d$ was controlled decreasing. When the estimated MS triggered the target, the $i_d$ control altered to the PI control mode whose command value was the normal operation of 0. The initial back-EMF was 75 V, and the $q$-axis voltage (back-EMF) at the end of the MS manipulation was 56 V. The corresponding PM flux after the manipulation was 0.089 Wb. Besides, $i_q$ was controlled zero in the magnetization and the demagnetization simulations. Therefore, the effectiveness of the $q$-axis current controller with the feed-forward compensation was verified.

VI. EXPERIMENTAL VERIFICATION

The proposed method was evaluated by experiments. An induction machine was mounted as the load machine. During normal operations, the test VFMM was controlled in the current-command mode. The sampling frequency and the PWM switching frequency were the same 10kHz. Variables in the control system, e.g., $i_d$, $i_q$, and the estimated MS, were recorded by a oscilloscope via digital-to-analog conversion. The machine phase current and the machine terminal voltages were recorded via current and voltage sensors. Because the MS estimation method calculates the current change ($di$), the current measuring noises will bring in additional error. The measure current was handled by a low pass filter. Considering the dynamic response of the MS estimation, the cut-off frequency was set by 500 Hz.

A. MAGNETIZATION EXPERIMENT

Fig. 10 presents the waveform in the magnetization experiment. The machine initial MS was zero and the target MS was 0.09 Wb. The load induction machine was controlled in the constant speed mode. The machine back-EMF was measured before and after the magnetization manipulation by terminating the PWM pulses. With the measured back-EMF, the no-load PM flux, i.e., the actual MS was calculated and the MS control accuracy was evaluated. The machine was dragged by the load machine at 1,000 rpm. The RMS value of the back-EMF before the manipulation was 2.61 V. The corresponding MS was 0.01 Wb (approximately zero). When the magnetization manipulation was triggered, the MS controller injected voltage of 20 V on the $d$-axis to activate the magnetization current. The zoomed view in Fig. 10 displays the detail process during the manipulation. $\Delta \psi_D/\Delta i_d$ was set to the maximum value in the MS estimation curve (Fig. 5) when $i_d$ was in the non-magnetization region, and the estimated MS was kept zero. When $i_d$ increased further, $\Delta \psi_D/\Delta i_d$ decreased because of the saturation effect.
B. DEMAGNETIZATION EXPERIMENT

Fig. 11 presents the waveform in the demagnetization experiment. The machine speed was 1,000 rpm. The back-EMF was measured as 25.1 V RMS before the demagnetization manipulation, showing the initial MS of 0.98 Wb. The target MS was set by 0.06 Wb. Because the machine saturation level is lower in the demagnetization, $\Delta \psi_D/\Delta i_d$ is approximately two times as the value in the magnetization (shown in Fig. 5). The injection voltage amplitude in the demagnetization was increased to 40 V, so that sufficient $\Delta i_d$ was able to identified and signal-to-noise ratio was increased. After the demagnetization was triggered, the negative voltage on the $d$-axis contributed to the increasing negative demagnetization current. The estimated MS decreased as $\Delta \psi_D/\Delta i_d$ increased. When the estimated MS reached the target 0.06 Wb, the MS controller transferred to the normal operation. The back-EMF after the demagnetization was 15.0 V RMS. The corresponding MS was 0.058 Wb, showing a good control accuracy with the target value of 0.06 Wb. Besides, the $q$-axis current was controlled to zero with little fluctuation in both the magnetization and the demagnetization experiments. The effectiveness of the current controller was also approved.

C. ON-LOAD MAGNETIZATION EXPERIMENT

The load induction machine was configured in the constant torque mode. The VFMM was controlled with a speed-loop. During normal operations, $i_d = 0$ control mode was implemented and the $q$-axis current was regulated with the PI controller in the speed-loop. The machine speed was controlled at 1,200 rpm. The load torque was configured as 1.0 Nm. The initial MS was 0.06 Wb and the target value was 0.10 Wb. Fig. 12 presents the experimental waveform. When the magnetization was started, a 20 V $u_{mag}$ was injected and $i_q$ was controlled to zero. When the estimated MS reached its target, the closed-loop MS control was terminated and the control system transferred to the normal operation. $i_d$ was controlled to zero and $i_q$ recovered to the speed-loop mode. The MS control accuracy was evaluated with the torque equation shown in (11):

$$T = \frac{3}{2} P \times MS \times i_q$$  (11)

where $P = 2$ is the pole pair. The RMS value of the phase current before and after the magnetization were 4.10 A and 2.41 A, respectively. Because the magnetization increases the PM flux, the current required to create the constant torque is reduced. Based on the condition of $i_d = 0$, the corresponding $i_q$ after the magnetization was derived as 3.41 A. Therefore, the MS was calculated and the value equaled 0.098 Wb, showing the good control accuracy.

The speed curve was recorded and displayed from the speed measurement in the control system. The torque was zero during the magnetization period because of the $i_q = 0$ control. The magnetization period, i.e., the time of the torque being zero was approximately 20 ms. The speed curve shows limited variation during this period. Because of
FIGURE 12. Experimental waveform of the magnetization manipulation with load condition.

FIGURE 13. Experimental waveform of magnetization manipulation at low speed of 90 rpm. (a) current and MS estimation. (b) line back-EMF.

the small manipulation time and the inertia in the rotating mechanical parts, the influence of the torque absence can be ignored.

D. MAGNETIZATION AT LOW SPEED

The load machine was configured again as the constant speed mode. The speed was set as 90 rpm. The initial MS was 0.03 Wb and the target MS was 0.06 Wb. Fig. 13 presents the experimental waveform. The injected magnetization voltage was the same of 20 V and contributed to the increase of $i_d$. The closed-loop MS control was terminated when the estimation value reached 0.06 Wb. The measured line back-EMF is shown in Fig. 13(b). The RMS value of the line back-EMF before and after the magnetization were 0.69 V and 1.41 V, respectively. Therefore, the corresponding MS after the magnetization was 0.061 Wb, showing the good control accuracy at the low speed. The effectiveness of the proposed method at low speed was verified.

VII. CONCLUSION

This article proposed an on-line magnetization state estimation and closed-loop control method. The proposed method regulates and injects voltage for the control of the magnetization or the demagnetization current. The injected voltage together with the current response are used as the source of the magnetization state estimation. The manipulation current changes the magnetization state and the machine saturation level, leading to the inductance non-linearity. The flux change rate, which is calculated by the injected voltage and the current response, reveals the inductance non-linearity in the magnetization state control. Therefore, the flux change rate is used for the magnetization state estimation. The signals required by the estimation exist in the magnetization state manipulation, so that the proposed method achieves self-sensing characteristic without additional signal injection. The proposed method was verified by the magnetization and the demagnetization experiments. The experimental results proved the control accuracy of the magnetization state control.

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