Enhanced Control and Power Management for a Renewable Energy Based Water Pumping System

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ABSTRACT-- The paper introduces a comprehensive dynamic analysis for a renewable energy based water pumping system. The complete system components are described in details. The components include a wind turbine power system, a permanent magnet synchronous generator (PMSG), a water pumping system and a battery. The storage system is used to enhance the power delivery under weak wind production which consequently enhances the system reliability. Considering the PMSG as the fundamental power unit in the system, a new predictive control procedure is presented to enhance the PMSG performance. To validate the effectiveness of the proposed control scheme, a detailed comparison is accomplished between the designed controller and other three traditional controllers to evaluate the most effective in between. A power management scheme is constructed to manage the power flow and ensuring a sufficient power delivery to the pumping system. The obtained results are presented and analyzed in details to compare between the dynamics of the four predictive controllers used to manage the generator operation. The results report that the formulated control scheme has the best performance in terms of the reduced fluctuations, low calculation capacity, structure simplicity and low currents THD. The obtained results also approve the validness of the designed power management strategy in balancing the power flow and stabilizing the DC bus voltage as well.

INDEX TERMS PMSG, predictive control, power management, battery storage, water pumping system, voltage control.

| Acronyms and symbols |
|----------------------|
| PC | Predictive control | $\omega_r$ | Rotor speed |
| MPC | Model predictive control | $\omega_e$ | Rotor electrical speed |
| DPC | Direct power control | $p$ | Pole pairs |
| WPS | Water pumping system | $\psi_d$ | PMSG flux |
| CCS | Continuous control set | $\psi_m$ | Rotor flux |
| FCS | Finite control set | $i_d$, $i_q$ | $d$-$q$ currents |
| MSC | Machine side converter | $u_{dcr}$, $u_{qcr}$ | $d$-$q$ voltages |
| CF | Cost function | $U_{dcr}$, $U_{qcr}^*$ | Real and command DC bus voltages |
| DOD | Depth of discharge | $C$ | Capacitor of DC bus |
| $S_f$ | Weighting scale | $c_s$, $c_p$ | Battery element capacitances |
| MPI | Motor-pump inverter | $R_s$, $R_x$, $R_t$ | Battery element resistances |
| IM | Induction motor | $U_{bat}$, $U_{bs}$, $U_{cs}$ | Bulk and surface capacitance voltages |
| HPS | Hybrid power system | $I_{bat}$, $I_b$, $I_s$ | Battery, bulk and surface currents |
| BSS | Battery storage system | $u_{m,bat}$, $I_{m,bat}$ | Battery modulated voltage and current |
| PSS | Power sharing strategy | $m_{bat}$ | Modulation index |
| PMS | Power management system | $R_p$, $R_s$ | Primary and secondary resistances of IM |
| UCS | Units control stage | $I_{tip}$, $L_{is}$ | Primary and secondary leakage inductances |
I. INTRODUCTION

The global warming and the depletion of natural energy sources urged the need to search for alternative solutions through utilizing the available renewable energy sources [1-3]. The sun, wind, geothermal and wave energies represent some forms of such renewable energy sources [4]. The renewable energy systems are considered as a promising solution to solve the electrification needs in the remote isolated areas [5, 6]. Among these types of renewable sources, the wind energy is paid great concern to electrify the isolated hilly areas in the forms of illuminating and sources, the wind energy is paid great concern to electrify isolated areas [5, 6]. Among these types of renewable energy systems are considered as a promising solution to solve the electrification needs in the remote isolated areas [5, 6]. Among these types of renewable energy sources [4]. The renewable energy systems are considered as a promising solution to solve the electrification needs in the remote isolated areas [5, 6]. Among these types of renewable energy sources [4].

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The global warming and the depletion of natural energy sources urged the need to search for alternative solutions through utilizing the available renewable energy sources [1-3].

The study has concerned with analyzing the relationship between the cost and system reliability [17]. The studies in [18-20], constructed efficient control systems to manage the operation of power converters to achieve maximum power extraction. In [21-23], different types of PMS are adopted to optimally operate each energy unit inside the hybrid system. The main task of the PMS is to obtain the optimal reference power of each system unit, which finally results in settling the DC link voltage with minimum fluctuations.

The generator is considered as the main important part in the wind generation system, which feeds the water pump. Thus, designing an effective control system that guarantees the proper operation is indispensable. Different machine types are used as a generation unit. The squirrel cage induction generator is used initially with the capability of parallel running [24,25]. However, the main drawback of this generator is the need of a separate source of reactive power (i.e. capacitor banks). Another used generator type is the slip-ring induction generator, known also as doubly fed induction generator (DFIG), which provided several advantages compared with the squirrel cage type [26,27]. The DFIG enabled the application of control from two sides: the stator or rotor terminals. Controlling the DFIG from rotor side provided an advantage of using low power scale converters, which saved the cost. In addition, the DFIG possessed the fault tolerant capability, which is realized via considering a certain modification in the
control algorithm. However, the maintenance cost of the DFIG is remarkable; this is in addition to the low efficiency due to the winding copper losses. The PMSG then came into consideration due to its multiple advantages [28,29], such as the ability to operate at high efficiency, solid structure and ability to work without gear systems. For these reasons, the surface mounted PMSG is used in the current study as the main generation unit.

Designing an effective control system to manage the PMSG operation is a vital requirement. The control targets for the PMSG include limiting the power, torque and current ripples. Limiting the torque ripples is specifically a vital need to suppress the shaft vibrations, which may harm the mechanical coupling system. In addition, limiting the current harmonics is another need to ensure high power quality. Different control schemes are adopted to manage the dynamics of PMSG; at beginning, the field oriented control (FOC) is used [30,31], in which an independent control of the active and reactive power or torque and flux is achieved through designing two separate inner current control loops. Sufficient steady state dynamic performance is achieved, however the response delay and system complexity were the most deficiencies of such technique. In order to avoid the FOC shortages, the direct torque control (DTC) is introduced and used with the PMSG [32,33]. The DTC can be implemented without using a modulation scheme (i.e. PWM) as in FOC. In addition, it can be applied directly in the stator frame which prevents the utilization of co-ordinate transformations as adopted in FOC. All of these features simplified the structure of DTC. Furthermore, the DTC succeeded in achieving a faster dynamic response compared with the FOC. Nonetheless, the main deficiency of the DTC was the high ripples and variable switching frequency because of the used hysteresis comparators. Another scheme which adopts a similar operation principle to the DTC is the direct power control (DPC) [34-36]. The DPC is a transpose of the DTC, which replaces the torque and flux control in DTC with active and reactive powers control, respectively. The DPC uses external control loops for the powers, which are evaluated directly from the measured voltages and currents. This made the DPC more robust than the DTC which depended on the model parameters to evaluate the torque and flux. To avoid the shortages in the FOC, DTC and DPC as well, different modern controllers are presented such as fuzzy predictive (FC) [37], sliding mode control (SMC) [38] and predictive control (PC) [39,40]. Among these controllers, the PC has succeeded in bringing the researchers’ interest due to its several advantages such as: simple structure, flexibility, ability to handle different system nonlinearities, ability to work without modulation stages and achieving different control targets at the same time.

Consequently, the PC theory is used to overcome the drawbacks of FOC, DTC and DPC via excluding the PI current controllers in FOC, and hysteresis comparators in DTC and DPC with only one simple cost function (CF), which is used to generate the reference signals after accomplishing an optimization process. After generating the reference signals using the CF, there are two possible ways to handle the references to the controlled item (i.e. the generator); one through using a continuous control set (CCS) PC which considers the average model of the converters and using a PWM [41,42], and the other via considering the finite control set (FCS) PC which considers the discrete converter model and selects from definite possible vectors without using a PWM [42,43]. Due to its simplicity, the FCS is used in our study to provide the reference signals to the PMSG terminals.

Thus, via applying the PC principle, the classic DTC and DPC are replaced with the model predictive DTC (MP DTC), and model predictive DPC (MP DPC), respectively. In the MP DTC, a CF incorporates the normalized flux and torque errors is utilized. This is in addition to using a scaling factor ($S_f$) that is used to balance the importance of flux control respecting to the torque control [44]. In the same manner, the MP DPC utilizes a CF which combines the standardized power errors besides using a weighting scale [45]. The MP DTC and MP DPC have succeeded in solving the problems of DTC and DPC, respectively via reducing the ripples content while maintaining the switching frequency within the permissible ranges. However, the ripples are still present and not completely eliminated; in addition, the high computation burden of the two predictive controllers is still a challenge. Furthermore, using a weighting scale $S_f$ in the MP DPC and MP DTC can affect the control if it is not appropriately identified. Attempts are made to avoid the wrong selection of $S_f$ through adopting online adaptation schemes [46,47]. Good results are obtained using the optimally selected $S_f$; however, the computation burden is further increased. Other control topologies turned their direction towards the elimination of $S_f$ from the CF such as model predictive current control (MP CC), which uses a CF consists of two comparable items (the errors of the d-q currents). Sufficient performance is obtained with the MP CC [48], however the computation burden is still remarkable due to the dependency on the model parameters.

The ripples in the MP DPC, MP DTC and MP CC schemes can be inferred to many reasons; one of these reasons is the utilization of only one voltage vector during the execution cycle, and it is possible that the absolute error of one variable deviates and causes the ripple increase. To solve this issue, different studies considered multiple vectors in the same sampling interval [49,50]. This helped effectively in suppressing the ripples, but the system complexity and consequently the computation capacity are inversely affected. Thus, formulating a CF without scale factor and using simple terms to save the computation time is a vital need. To fulfill these requirements, the current study proposed a predictive voltage control (PVC)
scheme which utilizes a CF deals with the voltage signals deviation. The actual voltage terms are obtained using the FCS principle; meanwhile the reference voltage terms are obtained using two designed PI regulators. Thus, the PVC does not utilize any estimated variables or a weighting scale, which saves the computation, and make the controller more robust. A comparison is carried out between the performances of PMSG using the the proposed predictive scheme and other three known predictive schemes to approve the superiority of the designed control algorithm.

Furthermore, the present study provides the design of an effective power management strategy to secure the power equilibrium between the different system units (Wind driven PMSG, battery storage unit, and water pumping system).

The presented study contributes to the literature by the following items

- The paper presents a comprehensive description of a hybrid power system (HPS) utilized for water pumping applications in remote areas.
- The design and modeling of all system parts are explained in details.
- An efficient power management strategy (PMS) is developed to balance the power flow in the hybrid system.
- A new PVC control scheme is presented to enhance the PMSG dynamics.
- A comprehensive comparison and performance analysis is accomplished between the proposed PVC and other three predictive schemes used previously with the PMSG.
- The formulated PVC showed high performance in comparison with the other predictive controllers overcoming the previous deficiencies and enhancing the PMSG dynamics.
- The present study can be considered as a base for future work in which additional energy sources (i.e. wave, fuelcell, solar) can be incorporated in favour of studying the system reliability.

The present study is arranged as: in Sec. II, the wind system including the PMSG is presented and described in details. In Sec. III, the battery model, the converter model and motor-pump unit model are presented and described in details. In Sec. IV, the supervisory hierarchical management system for the entire units is introduced and described in details. In Sec. V, the control of each system unit is presented. Sec. VI presents the test results and analyzes it. Finally, Sec. VII presents the conclusions of the study.

II. MODELING OF WIND TURBINE AND GENERATOR SYSTEM

A. Modeling of wind turbine

The system model of the wind turbine must be constructed precisely in order to emulate the wind speed variation. The model should incorporates the pitch angle ($\beta$) and MPPT control units. The MPPT is used to optimally exploit the wind power for the normal wind speed operation; this is realized via utilizing the optimal ratio ($\mu_{opt}$) [51]. On the other hand, the pitch control is applied to restrict the power when the wind speed is higher than the rated. The pitch control identifies a specific pitch angle ($\mu$) for each wind speed ($V_w$) variation with the help of a pitch servo system which utilizes a recorded $V_w$-$\beta$ curve. The ratio $\mu$ is defined by

$$\mu = \frac{r_{in}}{V_w} \tag{1}$$

where $r_{in}$ is the blade radius.

The turbine power coefficient $C_p$ is given by

$$C_p(\mu, \beta) = 0.53 \left(\frac{151}{\mu} - 0.058\beta - 0.002\beta^2 - 13.2 \right) e^{-\frac{23.9}{\mu}} \tag{2}$$

where $\mu = \frac{1}{\mu_{opt} - 0.005}$. The wind and turbine powers are evaluated by

$$P_w = \frac{1}{2} \rho A V_w^3$$

and

$$P_t = C_p P_w \tag{3}$$

where $A$ is the swept area, and $\rho$ is the density of the air. Using (1), (2) and (3), the shaft torque is given by

$$T_t = \frac{P_t}{\omega_t} = \frac{C_p \rho A V_w^3}{\omega_t} \tag{4}$$

The generator torque and speed are obtained by

$$T_g = \frac{T_t}{\alpha} \tag{5}$$

$$\omega_g = \alpha \omega_t \tag{6}$$

Furthermore, the turbine shaft dynamics is expressed by

$$T_t - g T_g - F_g \omega_t = \left(\frac{I_g}{\alpha} + I_g \omega_g \right) \frac{d \omega_g}{dt} \tag{7}$$

To activate the MPPT mode, an optimal value ($\mu_{opt}$) is imposed. Using these presumptions, the speeds reference signals to be utilized can be defined by
\[ \omega_z^* = \frac{\mu_{app} \omega}{R} \]  
(8)

\[ \omega_y^* = G \omega_z^* \]  
(9)

### B. Modeling of PMSG

The model of the PMSG can be represented discretely at instant \( kT \), by

\[ \frac{d\bar{q}_{g,k}}{dt} = \frac{1}{L_s} \left( \bar{u}_{qg,k} - R_l \bar{q}_{g,k} + \omega_s k L_s \bar{q}_{g,k} \right) \]  
(10)

\[ \frac{d\bar{d}_{g,k}}{dt} = \frac{1}{L_s} \left( \bar{u}_{dg,k} - R_l \bar{d}_{g,k} - \omega_s k L_s \bar{d}_{g,k} - \omega_s \psi_{m,k} \right) \]  
(11)

where \( \omega_s = \rho \omega_g \) is the electrical generator speed.

The mechanical subsystem dynamics of the PMSG can be expressed by

\[ \frac{d\omega_g}{dt} = 1 \left( T_{t,k} - T_{g,k} - T_{j,k} \right) \]  
(12)

The PMSG torque can be evaluated by

\[ T_{g,k} = 1.5 p \psi_{m,k} k l_{qg,k} \]  
(13)

The data specifications of the wind conversion system are shown in Table 4, in appendix A.

### III. MODELING OF BATTERY, CONVERTERS, DC BUS AND MOTOR-PUMP UNIT

#### A. BATTERY MODELING

The battery is utilized to handle the surplus power and compensate the wind energy shortage. In addition, to avoid the system malfunctions due to the wind intermittence behavior, a battery storage system must be incorporated. As stated in [52,53], the battery voltage balance can be represented by

\[ U_{bat,k} = I_{bat,k} R_t + I_{b,k} R_e + U_{ch,k} = I_{bat,k} R_t + I_{s,k} R_s + U_{cs,k} \]  
(14)

The battery voltage dynamics can be also expressed in the matrix form by

\[
\begin{bmatrix}
\frac{dU_{ch,k}}{dt} \\
\frac{dU_{cs,k}}{dt} \\
\frac{dU_{bat,k}}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
Z_{11} & Z_{12} & Z_{13} \\
Z_{21} & Z_{22} & Z_{23} \\
Z_{31} & Z_{32} & Z_{33}
\end{bmatrix}
\begin{bmatrix}
U_{ch,k} \\
U_{cs,k} \\
U_{bat,k}
\end{bmatrix}
+ 
\begin{bmatrix}
\frac{R_s}{C_s} \\
\frac{R_g}{C_s} \\
\frac{R_e + R_s}{B}
\end{bmatrix}
I_{bat,k}
\]
(15)

where \( Z_{11} = -\frac{1}{C_b(R_e + R_s)} \), \( Z_{12} = \frac{1}{C_b(R_e + R_s)} \), \( Z_{13} = 0 \), \( Z_{21} = \frac{1}{C_s(R_e + R_s)} \), \( Z_{22} = -\frac{1}{C_s(R_e + R_s)} \), \( Z_{23} = 0 \), \( Z_{31} = \frac{R_s}{C_b(R_e + R_s)^2} + \frac{R_g}{C_s(R_e + R_s)^2} + \frac{R_e}{C_s(R_e + R_s)^2} \), \( Z_{32} = 0 \), \( Z_{33} = \frac{C_b R_e}{C_b(R_e + R_s)} - \frac{1}{C_s(R_e + R_s)} \).

The battery specifications are presented in Table 5 in Appendix A.

#### B. Modeling of power converters and DC bus

Figure 1 illustrates an overview of the wind generation based water pumping system. The system consists of three main parts: the wind turbine system, the battery system and the water pumping system, in addition to the DC link unit which represents the power port that links the different units. In the figure, it can be noticed that there is a machine side converter (MSC) which acts as a controlled rectifier to handle the generator power to the other units through the DC link. Also there is the motor-pump inverter (MPI) which regulates the operation of the IM that manages the pump operation. There is also a bi-directional DC/DC power converter which is used to regulate the battery operation.

Consequently, the models of these converters must be constructed to ensure the proper power flow. Generally, the MSC and MPI have a faster dynamic compared with the wind dynamics. For this reason, it is appropriate to identify solely the low-operating frequency of the converters variables in order to describe the wind system dynamics [54,55]. Consequently, a continuous equivalent converter model is used to represent the current and voltage dynamic states.

According to these assumptions, the modulated voltages of the MSC are determined by

\[
\begin{bmatrix}
\bar{u}_{d,q_k} \\
\bar{u}_{q,q_k}\n\end{bmatrix}
= 
\begin{bmatrix}
\bar{u}_{d,c_k} \\
\bar{u}_{c,c_k}\n\end{bmatrix}
+ \frac{\bar{u}_{d,q_k}}{2}
\]
(16)
where $U_{dc}$ is the DC bus voltage, and $u_{d,k}^g$ and $u_{q,k}^g$ are the MSC control signals.

where $i_{d,k}$ and $i_{q,k}$ are the IM $d$-$q$ currents. Meanwhile, $e_{d,k}^g$ and $e_{q,k}^g$ are the MPI inverter control signals.

In addition, the MPI modulated voltages can be calculated by

$$
\begin{bmatrix}
    e_{d,k}^g \\
    e_{q,k}^g
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
    u_{d,c,k} \\
    u_{q,c,k}
\end{bmatrix}
$$

(19)

FIGURE 1. Layout of hybrid power system (HPS) system

Then, the modulated generator current $I_{m1}$ shown in Fig. 1 can be evaluated as following

$$
I_{m1,k} = \frac{1}{2} (u_{d,k}i_{d,k} + u_{q,k}i_{q,k})
$$

(17)

Similarly, the modulated current of the MPI inverter ($I_{m,inv}$), can be expressed by

$$
I_{m,inv,k} = \frac{1}{2} (e_{d,k}^g i_{d,k} + e_{q,k}^g i_{q,k})
$$

(18)

From (17) and (18), the dynamics of DC link can be described by the following relationship

$$
C \frac{du_{dc,k}}{dt} = I_{dc,k} = I_{m1,k} + I_{m,bat,k} - I_{m,inv,k}
$$

(22)

The bi-directional DC/DC power converter illustrated in Fig. 1 is also utilized to regulate the charging/discharging process for the battery storage system (BSS). An inductor $L_{bat}$ is used to attenuate the battery current harmonics. Similar to the MSC and MPI, a continuous model is used for the bi-directional converter, and consequently the modulated voltage and current for the DC/DC converter are calculated by

$$
U_{m,bat,k} = m_{bat,k} U_{dc,k}
$$

(20)

$$
I_{m,bat,k} = m_{bat,k} I_{bat,k}
$$

(21)

The control systems design for the MSC and MPI power converters is comprehensively explained in Sec. V.
B. Modeling of motor-pump unit

The pump is operated with the help of an IM. The IM equivalent model can be constructed as given in [56], in which all variables are defined in a frame rotates with a similar speed to the rotor flux vector \( \omega_{\psi_r} \).

Then, the IM dynamics can be described by

\[
\frac{d\psi_{rf}^{\text{ref}}}{dt} = \psi_{rf}^{\text{ref}} - R_p i_{rf}^{\text{ref}} - j \omega_{\psi_r} \psi_{df}^{\text{ref}}
\]

(23)

\[
\frac{d\psi_{rf}}{dt} = -R_f i_{rf}^{\text{ref}} - j \left( \frac{\omega_{\text{slip}}}{\omega_{\psi_{dr}^{\text{ref}}} - \omega_m} \right) \psi_{df}^{\text{ref}}
\]

(24)

\[
\frac{d\omega_{me}}{dt} = \frac{n_p}{J_m} (T_{e,k} - T_{k})
\]

(25)

where \( \omega_m = n_p \omega_m \) is the electrical rotor speed, \( n_p \) is the pole pairs and \( \omega_m \) is the mechanical rotor speed. The superscript \( 'r' \) refers to the rotor flux rotating frame.

The torque \( T_{e,k} \) can be evaluated by

\[
T_{e,k} = 1.5 n_p \frac{L_m}{\sigma L_r} \psi_{df}^{\text{ref}} \times \psi_{df,k}^{\text{ref}} = 1.5 n_p \frac{L_m}{\sigma L_r} \left( \psi_{qf,k}^{\text{ref}} \psi_{df,k}^{\text{ref}} - \psi_{df,k}^{\text{ref}} \psi_{qf,k}^{\text{ref}} \right)
\]

(26)

where \( \sigma = 1 - (L_r^2 / L_s L_r) \) is the leakage factor.

The output mechanical power on the IM shaft equals the absorbed power by the pump, which can be evaluated by

\[
P_{\text{pump},k} = K_L \omega_m^3
\]

(27)

where \( K_L \) is the speed-torque coefficient.

The beneficial pump power \( (P_h) \) can be represented by

\[
P_{h,k} = \eta P_{\text{pump},k} = D g H_k Q_k
\]

(28)

where \( D \) is the density \( (k_g/m^3) \), \( g \) is the gravity acceleration \( (m^2/s) \).

The water volume can be calculated as

\[
V_k = Q_k \Delta T
\]

(29)

To evaluate the water level \( (H) \) inside the tank, the following relationship is used

\[
\frac{dV_k}{dt} = S \frac{dH_k}{dt} = Q_{in,k} - Q_{out,k}
\]

(30)

where \( Q_i \) and \( Q_o \) are the water flow entering and leaving the tank, respectively. And \( S \) is the tank area.

IV. SUPERVISORY HIERARCHICAL CONTROL

To control and supervise the operation of the hybrid power system (HPS), a supervisory hierarchical control is represented as shown in Fig. 2. In this system, there are three main phases that can be described as follows

- In the first phase, a strategy for sharing the power (PSS) is used to generate the command power signals for each unit in the HPS in order to fulfill the motor-pump unit requirements. The power management strategy (PMS) is also implemented in this step to achieve the balance between the power production and consumption.

- In the second phase, the internal control of each system unit is applied. So it is entitled ‘units control stage’ (UCS). During this step, the modulation indices \( (m) \) for each power converter used in the HPS are generated.

- In the third phase, the switching management unit (SMU) is used to provide the switching signals for the specified converters.

A. Power sharing strategy (PSS)

Delivering the power to the water pump must follow the operation strategy and the connection architecture. Therefore, to maintain the system power balance, a PSS strategy is structured. The PSS consists of two subsystems: the power control level (PCL) and the power management strategy (PMS).

A.1. Power control level (PCL)

As shown in Fig. 2, the PCL is used to provide four reference values: generator torque reference \( (T_g^*) \), battery current reference \( (I_{bat}^*) \), DC link current reference \( (I_{dc}^*) \), and IM speed reference \( (\omega_m^*) \). These references are extracted from the interchanged power between the system units and the DC link. The power flow management is realized via utilizing the model expressions in order to identify the reference power \( (P_{pump}^*) \) besides the DC link reference power \( (P_{dc}^*) \) while estimating the available wind power to be delivered to the generator \( (P_g^*) \).
A.2. Power management strategy (PMS)

The PMS strategy is concerned with dispatching the powers between the various system units to fulfill the power requirements of the pumping system. The generator power ($P_g$), the actual ($H$) and desired ($H^*$) heights in the water sink tank, and the battery SOC are the inputs to the PMS. These data besides the function of the battery storage system (BSS) (even with the excess or lack of developed power) will identify the system working modes as shown in Fig. 3. Essentially, the specified modes are depicted to ensure tracking the desired power levels of the wind turbine, the pump and the BSS system. This is in addition to ensuring the stability of the pump power flow respecting to the DC bus voltage, the limits of BSS ($SOC_{max}, SOC_{min}$) and pump specifications as obviously shown in Fig. 3.
 FIGURE 3. Power management system (PMS)

The detailed description of each operating mode in Fig. 3 is presented as follows:

A.2.1. Operating mode 1

In this mode, the water level \( H \) inside the tank is higher or similar to the predefined height \( H^* \) (Tank is filled). Furthermore, the power delivered is higher than the demanded by the pump, that is here zero \( P_{\text{pump}}^* = 0 \), and the battery is with full charge \( S_O C > S_O C_{\text{max}} \). As a result, the surplus power is disregarded without operating the pump. The mathematical relationships that represent the first mode are expressed by

\[
P_{\text{pump}}^* = 0 \quad \text{and} \quad P_{\text{bat}}^* = 0
\]  

(31)

A.2.2. Operating mode 2

This mode is relevant to the case at which the water tank is not completely occupied, with the generated power from the PMSG larger than the demanded power and with a SOC lower than the maximum SOC \( (S_O C < S_O C_{\text{max}}) \). Consequently, the powers at this stage are represented as

\[
P_{\text{pump}}^* = P_{\text{pump},\text{nom}} \quad \text{and} \quad P_{\text{bat}}^* = P_g
\]  

(32)

A.2.3. Operating mode 3

In this mode, the generated power is adequate, the water reservoir is not totally occupied; in addition, the battery charging is not complete. The system continues to work in order to fill the tank and in case of having a surplus power, the BSS will absorb it as long as the battery SOC stays in the permissible range. Therefore, the battery is under the charging mode. The power relationships in this mode are described by

\[
P_{\text{pump}}^* = P_{\text{pump},\text{nom}} \quad \text{and} \quad P_{\text{bat}}^* = P_g - P_{\text{pump},\text{nom}} + P_{\text{dc}}
\]  

(34)
A.2.6. Operating mode 6

In this stage, the pump is operated completely from the BSS because of missing the wind power. The battery is running under the discharging mode. As a result, the power balance can be described by

\[ P_{\text{pump}}^* = P_{\text{pump, nom}} \quad \text{and} \quad P_{\text{bat}}^* = -P_{\text{pump, nom}} - P_{dc} \]  \hspace{1cm} (35)

A.2.7. Operating mode 7

In this mode, the water pump is disconnected from the HPS, and the powers can be expressed by

\[ P_{\text{pump}}^* = 0 \quad \text{and} \quad P_{\text{bat}}^* = 0 \]  \hspace{1cm} (37)

V. UNITS CONTROL STAGE (UCS)

As illustrated in Fig. 2, the UCS contains the separate control for each unit in the HPS system. Thus, the following subsections are devoted to provide a detailed description for the used control strategies.

A. Control of PMSG

The PMSG and its wind turbine driving system constitute the core of the HPS, and for this reason, different control algorithms are utilized to analyze the PMSG and outline the most appropriate in between to achieve the optimal power capturing while ensuring high power quality through limiting the ripples and generated current harmonics. Four predictive controllers are formulated to manage the PMSG performance. The mechanism by which each control works is described as follows:

A. 1. Design of MP DPC for PMSG

The MP DPC operation stands on controlling the active and reactive powers of the PMSG. The core operation of the MP DPC is performed by a CF that handles the deviations of the actual predicted powers from their references. The CF also uses a scaling factor \( S_T = \frac{P_{\text{nom}}}{Q_{\text{nom}}} \) to give a weight for the reactive power corresponding to the active power. Consequently, the MP DPC cost function is represented by

\[ C_{k+1} = \left| T_{g, k+1}^* - \tilde{T}_{g, k+1} \right|^2 + S_T |\psi_{g, k+1}^* - \tilde{\psi}_{g, k+1}|^2 \]  \hspace{1cm} (38)

where the superscript \(^*\) identifies the voltage index. The reference power \( Q_{g, k+1}^* \) is set to zero, while the reference active power \( P_{g, k+1}^* = T_{g, k+1}^* \omega_{g, k+1}^* \) is derived from the wind turbine driving system. Furthermore, the predicted powers \( \tilde{P}_{g, k+1} \) and \( \tilde{Q}_{g, k+1} \) can be evaluated by

\[ \tilde{P}_{g, k+1} = 1.5(\tilde{u}_{dg, k+1} \tilde{i}_{dg, k+1} + u_{ag, k+1} i_{ag, k+1}) \]  \hspace{1cm} (39)

\[ \tilde{Q}_{g, k+1} = 1.5(\tilde{u}_{ag, k+1} i_{dg, k+1} - u_{dg, k+1} i_{ag, k+1}) \]  \hspace{1cm} (40)

where \( i_{dg, k+1} \) and \( i_{ag, k+1} \) are the predicted d-q currents of PMSG which are calculated using (10) and (11) as following

\[ i_{dg, k+1} = i_{dg, k} + \left( \frac{di_{dg, k}}{dt} \right) T_s \]  \hspace{1cm} (41)

\[ i_{ag, k+1} = i_{ag, k} + \left( \frac{di_{ag, k}}{dt} \right) T_s \]  \hspace{1cm} (42)

The \( d-q \) voltage components \( u_{dg, k+1} \) and \( u_{ag, k+1} \) can be evaluated by

\[ u_{dg, k+1} = u_{dg, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (43)

Thus, after calculating the terms of (38), the control starts to evaluate the cost function value at each instant and identifies the first voltage vectors that minimize its value and apply to the machine terminals. The system layout of the MP DPC is shown in Fig. 4.

A. 2. Design of MP DTC for PMSG

The MP DTC operation aims to managing the flux and torque of the PMSG. Accordingly, the controller utilizes a CF combining the flux and torque errors, through which the optimal voltages can be obtained. The CF substitutes the optimal voltages can be obtained. The CF combines the flux and torque errors, through which the optimal voltages can be obtained. The CF substitutes the optimal voltage components \( u^* \) and \( \psi^* \) of PMSG which are calculated using (10) and (11) as following

\[ u_{dg, k+1} = u_{dg, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (44)

\[ u_{ag, k+1} = u_{ag, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (45)

The \( d-q \) voltage components can be evaluated by

\[ u_{dg, k+1} = u_{dg, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (46)

\[ u_{ag, k+1} = u_{ag, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (47)

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A. 2. Design of MP DTC for PMSG

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\[ u_{dg, k+1} = u_{dg, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (48)

\[ u_{ag, k+1} = u_{ag, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (49)

The \( d-q \) voltage components can be evaluated by

\[ u_{dg, k+1} = u_{dg, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (50)

\[ u_{ag, k+1} = u_{ag, k} + \left( \frac{u_{ag, k}}{\Delta T} \right) \frac{\Delta T}{\Delta T} T_s \]  \hspace{1cm} (51)
The torque reference $T_{g,k+1}^*$ is provided by the wind power system explained earlier in Sec. II; while the flux reference $\psi_{g,k+1}^*$ is calculated utilizing the $d$-$q$ command currents as following:

$$\psi_{g,k+1}^* = \sqrt{(L_s i_{ag,k+1} + \psi_{m,k+1})^2 + (L_s i_{aq,k+1})^2}$$  \hspace{1cm} (44)$$

The current reference $i_{ag,k+1}^*$ is kept to zero; while the reference $i_{aq,k+1}^*$ is calculated by:

$$i_{ag,k+1}^* = \frac{T_{g,k+1}}{1.5P\psi_{m,k+1}}$$  \hspace{1cm} (45)$$

The predicted torque and flux signals in (43) are computed by:

$$\tilde{T}_{g,k+1} = 1.5P\psi_{m,k+1}i_{ag,k+1}$$  \hspace{1cm} (46)$$

$$\tilde{\psi}_{g,k+1} = \sqrt{(L_s \tilde{i}_{ag,k+1} + \psi_{m,k+1})^2 + (L_s \tilde{i}_{aq,k+1})^2}$$  \hspace{1cm} (47)$$

The predicted currents $\tilde{i}_{ag,k+1}$ and $\tilde{i}_{aq,k+1}$ are calculated using (41).

Accordingly, the MP DTC starts to evaluate (43), and identifies the optimal voltage which minimizes (43) and apply it. The MP DTC schematic diagram is shown in Fig. 5.

A. Design of MP CC for PMSG

The MP CC operation aims to regulating the $d$-$q$ current components of PMSG in order to indirectly control the flux and torque, respectively [48]. The MP CC approach replaces the PI current regulators used in classic vector control approach with a CF which combines the deviations of the $d$-$q$ currents as following:

$$C_{g,k+1} = |i_{ag,k+1}^* - \tilde{i}_{ag,k+1}| + |i_{aq,k+1}^* - \tilde{i}_{aq,k+1}|$$  \hspace{1cm} (48)$$

The current reference $i_{ag,k+1}^*$ is kept to zero to ensure unity pf operation; meanwhile the reference $i_{aq,k+1}^*$ is obtained using (45). Alternatively, the predicted currents $\tilde{i}_{ag,k+1}$ and $\tilde{i}_{aq,k+1}$ can be evaluated using (41).

After evaluating the value of (48) at each sampling time, the MP CC specifies the optimal voltage value which makes (48) with zero value and apply it. A layout for the MP CC approach is shown in Fig 6.
A. 4. Proposed PVC for PMSG

The main deficiency in the CF used by the MP DPC and MP DTC schemes is the utilization of estimated variables, which consume the time, and consequently increases the number of commutations. This is in addition to the issue of scaling factor. As an attempt to avoid these deficiencies, a predictive voltage control (PVC) technique is presented. The designed PVC utilizes a CF of two matched parts without adding a weighting scale. In addition, the variables used in the cost function do not require an estimation, which saves the computation time and limits the switching losses. The cost function of the proposed PVC can be expressed by

\[ C_{k+1} = |u_{dg,k+1} - u_{dg,k+1}^*| + |u_{aq,k+1} - u_{aq,k+1}^*| \]  

(49)

The FCS is used to generate the actual voltages \( u_{dg,k+1} \) and \( u_{aq,k+1} \) in (49). This is accomplished via processing the switching states generated from the controller without using a PWM scheme. Furthermore, the reference voltages \( u_{dg,k+1}^* \) and \( u_{aq,k+1}^* \) are determined using a designed flux and torque regulators. The tuning of these regulators is accomplished as follows:

Considering the flux orientation concept, the PMSG flux should be aligned to the \( q \)-axis of the rotating frame. Consequently, the following relationships are obtained:

\[ \psi_{dg,k+1} = |\bar{\psi}_{g,k+1}| \text{ and } \psi_{aq,k+1} = 0.0 \]  

(50)

By replacing from (50) into (10) and (11), it gives

\[ u_{dg,k+1} = R i_{dg,k+1} + \frac{d|\psi_{g,k+1}|}{dt} \]  

(51)

\[ u_{aq,k+1} = R i_{aq,k+1} + \omega_{s,k+1} |\bar{\psi}_{g,k+1}| \]  

(52)

From (51) and by neglecting the voltage drop on \( R \), the flux can be controlled thoroughly by the voltage \( u_{dg,k+1} \).

From Fig. 7 which represents the space displacements of the stator flux \( \bar{\psi}_{g,k+1} \) and rotor flux \( \bar{\psi}_{m,k+1} \) vectors, the angular frequency of stator flux (\( \omega_{s,k+1} \)) can be calculated by

\[ \omega_{s,k+1} = \omega_{g,k+1} + \frac{d\delta_{k+1}}{dt} \]  

(53)

where \( \delta_{k+1} \) is the torque angle.

The current \( i_{aq,k+1} \) in (52) can be calculated by

\[ i_{aq,k+1} = \frac{\tau_{g,k+1}}{1.5p|\bar{\psi}_{g,k+1}|} \]  

(54)

Then, by substituting from (53) and (54) into (52), it results in

\[ u_{aq,k+1} = R \left( \frac{\tau_{g,k+1}}{1.5p|\bar{\psi}_{g,k+1}|} + \left( \omega_{g,k+1} + \frac{d\delta_{k+1}}{dt} \right) |\bar{\psi}_{g,k+1}| \right) \]  

(55)

From (55), it is obvious that the torque management can be achieved via managing the \( q \)-axis voltage \( u_{aq,k+1} \).

Accordingly, the command voltages required by (49) can be determined using the following expressions.

\[ \begin{aligned} & \psi_{g,k+1} = \psi_{g,k+1}^* \\ & \psi_{m,k+1} = \psi_{m,k+1}^* \end{aligned} \]  

FIGURE 7. Allocation of fluxes in space
\[ u_{d\alpha,k+1} = \left( K_{P\psi} + \frac{K_{T\psi}}{s} \right) \left( \psi_{g,k+1} - \tilde{\psi}_{g,k+1} \right) \]  
\[ (56) \]

\[ u_{q\beta,k+1} = \left( K_{P\psi} + \frac{K_{T\psi}}{s} \right) \left( T_{g,k+1}^* - T_{g,k+1} \right) \]  
\[ (57) \]

where \( K_{P\psi}, K_{T\psi}, K_{PT} \) and \( K_{IT} \) are the parameters of flux and torque controllers, accordingly.

Figure 8 formulates the closed flux control loop, which is evaluated by deriving the Laplace transform of (51).

![FIGURE 8. Closed loop flux control model](image)

In Fig. 8, the plant and controller transfer functions \( G_{P\psi}(s) \) and \( G_{C\psi}(s) \) are defined as

\[ G_{P\psi}(s) = \frac{1}{s} \]  
\[ (58) \]

\[ G_{C\psi}(s) = \frac{K_{P\psi}s + K_{T\psi}}{s} \]  
\[ (59) \]

Accordingly, from (58) and (59), the transfer function which governs the flux controller can be then evaluated by

\[ G_{\psi}(s) = \frac{G_{P\psi}(s)G_{C\psi}(s)}{1 + G_{P\psi}(s)G_{C\psi}(s)} \text{ or } \frac{K_{P\psi}s + K_{T\psi}}{s^2K_{P\psi}s + K_{T\psi}} \]  
\[ (60) \]

The denominator of (60) formulates the characteristic equation of the controller, which must be with negative roots in order to ensure stable dynamics. Accordingly, the following is obtained

\[ s^2 + K_{P\psi}s + K_{T\psi} = 0 \]  
\[ (61) \]

Alternatively, the dynamics of a second order model is expressed by

\[ s^2 + 2\omega_n\xi s + \omega_n^2 = 0 \]  
\[ (62) \]

where \( \omega_n \) and \( \xi \) are the system frequency and damping factor.

By comparing, (61) and (62), the coefficients of flux regulator are obtained by

\[ K_{P\psi} = 2\omega_n\xi \quad \text{and} \quad K_{T\psi} = \omega_n^2 \]  
\[ (63) \]

In a same way, the gains of torque controller can be determined via analyzing (55).

From Fig. 8, the torque can be evaluated by

\[ T_{g,k+1} = \frac{1.5P}{L_s} \left[ \dot{\psi}_{m,k+1} \right] \left[ \tilde{\psi}_{g,k+1} \right] \sin \delta_{k+1} \]  
\[ (64) \]

By differentiating (64) and adding the result to (55), it gives

\[ u_{qg,k+1} = \frac{RT_{g,k+1}}{1.5P[\tilde{\psi}_{g,k+1}]} + \left( \frac{dT_{g,k+1}}{dt} \right) \left[ \tilde{\psi}_{g,k+1} \right] \]  
\[ (65) \]

where \( Y_T = K_T \cos \delta_{k+1} \).

Applying the Laplace transform on (65), it gives

\[ u_{gq,k+1}(s) = \left( \frac{R}{1.5P[\tilde{\psi}_{g,k+1}(s)] + \frac{1}{Y_T(s)}} \right) \tilde{\psi}_{g,k+1}(s) + \omega_{g,k+1}(s) \tilde{\psi}_{g,k+1}(s) \]  
\[ (66) \]

Using (66), the torque control loop can be formulated as in Fig. 9. Where, \( G_{PT}(s) \) and \( G_{CT}(s) \) are the transfer functions of the plant and torque controllers. The functions can be evaluated as following

\[ G_{PT}(s) = \frac{1.5P[\tilde{\psi}_{g,k+1}(s)]Y_T(s)}{RT_T(s) + 1.5P[\tilde{\psi}_{g,k+1}(s)]s} \]  
\[ (67) \]

![FIGURE 9. Closed loop torque control model](image)
From (62) and (69) and by comparison, the coefficients of the torque controller are determined as follows:

\[
K_p = \frac{3p|\tilde{\psi}_{g,k+1}|^2}{1.5p|\tilde{\psi}_{g,k+1}|y_T}, \quad \text{and} \quad K_I = \frac{\omega_0^2|\tilde{\psi}_{g,k+1}|}{y_T} \tag{70}
\]

After designing the regulators, the reference voltages \(u_{ax,k+1}^*\) and \(u_{ag,k+1}^*\) can be obtained and used in (49). The structure of the proposed PVC is illustrated in Fig. 10.

In order to give a detailed view on the operation mechanism of the proposed PVC, a flow chart is illustrated in Fig. 11 which outlines the implementation stages of the designed control.

**B. Control of BSS and DC link**

When a power shortage or a surplus is present, the BSS is used to regulate the power exchange among the pumping system and the PMSG. As a result, it smoothes out the wind power fluctuations to ensure that the entire system performs properly. A series of batteries, an inductor \(L_{bat}\) acts as a filter and a bi-directional converter formulate the BSS. Fig. 12 illustrates how to manage the power converter and battery current variation. To provide the modulated output battery voltage displayed in Fig. 12 and the duty cycles of the bi-directional converter, an internal control loop for the battery current is utilized. Due to its slow dynamic, the DC bus voltage is assumed as a constant value. As a result, an outer control loop is used to ensure that the DC link maintains a decent approximation of its reference value regardless of the power exchange between the different units of HPS. Managing the DC voltage plays a significant role in achieving more stable and enhanced system operation. As a result, a PID controller whose input is the battery current error is utilized to compensate the voltage deviation as illustrated in Fig. 12. The design of the two PID controllers used in Fig. 12 is described in details in the appendix.

**C. Control Motor-Pump unit**

The water pump operation is managed using an IM drive which is controlled using a field oriented control (FOC) scheme in which the \(d\)-axis of synchronous rotating frame is aligned with the rotor flux vector \((\tilde{\psi}_{dr,k} = |\tilde{\psi}_r|\) and \(\tilde{\psi}_{qr,k} = 0.0\)). Furthermore, the motor torque is controlled independently using the \(q\)-axis current \((i_{eq,k})\). On the other side, the rotor flux dynamics is managed using the \(d\)-axis current \((i_{ds,k})\). Consequently an independent control of the torque and flux can be achieved, and the IM dynamics can
be managed. The relationships between the rotor flux and torque from one side and the direct and quadrature axes stator currents on the other side under FOC are expressed by

$$\psi_{dr,k} = \frac{L_m}{1+\tau_r}i_{ds,k}$$  \hspace{1cm} (70)$$

$$T_{e,k} = 1.5n_p \frac{L_m}{\tau_r}\psi_{dr,k}i_{qs,k}$$  \hspace{1cm} (71)$$

where $$\tau_r$$ is the IM rotor time constant.

The management of the IM variables (speed, flux and currents) is achieved through utilizing two PI current controllers in order to keep the actual values following their references.

The parameters of the IM and the PI current controllers’ gains are given in Table 1.

Up to this stage, all components of the HPS and its power management and sharing strategy, in addition to the relevant control of each system unit are described in details. In the next section, the test results are demonstrated in which the PMSG and other HPS units dynamics are evaluated considering the previously described predictive controllers with the PMSG, and considering the PMS of all units as well.

**FIGURE 11.** Control scheme for BSS and DC bus

The parameters of the IM and the PI current controllers’ gains are given in Table 1.
VI. TEST RESULTS

The performance analysis of the HPS and its power management strategy (PMS) and internal unit controls is presented in this section. Firstly, the PMS performance with the four predictive controllers used by the PMSG is introduced. The following illustrations present the combined power flow diagrams for the four internal predictive controllers. In addition, the operating modes related to each power change are also shown. Figs. 13, 14, 15 and 16 show the combined power flows under the four predictive schemes, while Figs. 17, 18, 19, 20, 21, 22 and 23 show the operating modes. These results are considered as a validation to the designed PMS and the sequence of operation modes described previously in Sec. A.2 and Fig. 3.

In the combined power diagrams, the PMSG power, the battery power, the pump power and the excess power are illustrated. By checking the relevant operating modes figures, it can be realized that at majority of times, the developed PMSG power are covering the pump power requirements. Meanwhile, power flow during the other time intervals can be summarized as in Table 2.

| Time intervals | Power flow state | Time intervals | Power flow state |
|----------------|-----------------|----------------|-----------------|
| 1.15→3.5 s, 10→12.2 s, 20.4→23.5 s, 30→33.5 s, 40→43.5 s, 50→53.5 s, 60→63.5 s, 80→83.5 s, 90→91.4 s, 18.9→20 s, 65.6→73.5 s, 73.5→80 s, 86.3→90 s, 92.5→120 s, 3.6→10 s, 13.5→18.9 s, 23.5→30 s, 33.5→40 s, 43.5→50 s, 53.5→60 s, 63.5→65.6 s, 83.5→86.3 s. | The battery storage system (BSS) compensates the power shortage to ensure operating the pump at its nominal power. | 3.6→10 s, 13.5→18.9 s, 23.5→30 s, 33.5→40 s, 43.5→50 s, 53.5→60 s, 63.5→65.6 s, 83.5→86.3 s. | During these intervals, the excess power is rejected. The HPS during these times is in oversize condition. | From the analysis of power flow states and the related operating modes, it can be confirmed that the designed PMS has approved its ability in achieving a balanced power exchange between the different units of the HPS.

From the analysis of power flow states and the related operating modes, it can be confirmed that the designed PMS has approved its ability in achieving a balanced power exchange between the different units of the HPS.
Before analyzing the dynamics of the four predictive controllers used for PMSG; the wind speed profile, the generator speed, the turbine power coefficient ($C_p$), the ratio ($\mu$) and the angle ($\beta$) profiles are primarily presented in Figs. 24, 25, 26, 27 and 28, respectively. These captured behaviors are presented for the four predictive controllers. It is observed that the generator speed is tracking the change in wind speed, also it can be noticed that the tip speed ratio ($\mu$) is maintained to its optimal value in order to achieve optimal power extraction. It can be noticed also that the pitch angle control is activated when the wind speed exceeds its nominal value. This is observed from the values of $C_p$ and $\beta$ which exhibit a decrease and an increase, respectively in order to restrict the turbine power.
A. Internal units control analysis

A.1. Performance analysis with MP DPC

After analyzing the performance of PMS and the control of wind turbine system; in the current test, the MP DPC control technique [45] is tested for regulating the generated power from the wind driven PMSG. The validity of the MP DPC technique is approved through ensuring the tracking of actual active and reactive powers, $d$-$q$ stator current components and generator torque to their corresponding reference values. This has been presented in Figs. 29, 30, 31, 32 and 33, respectively. The active power tracks the wind speed dynamics, meanwhile the reactive power is kept at zero value. The $q$-axis stator current and also the torque are following the change in active power, meanwhile the $d$-axis current is held appropriately at zero. However a good tracking is achieved, but the ripples are noticeable in the controlled PMSG variables and in battery power and current as well.

Figure 34 shows the PMSG currents which follows in its dynamic the wind variation. The battery variables; specifically the battery power, battery current and its state of charge (SOC) are illustrated respectively in Figs. 35, 36, and 37.
The pump power, the IM motor-pump torques, the water flow and water tank level are also shown in Figs. 38, 39, 40 and 41, respectively. It can be noticed from these figures that each time the water height is reduced below its reference (3.5 m), the PMS activate the power delivery to the pumping system and the pump starts to operate reciprocally to compensate the water shortage. The IM torque is also properly controlled to balance the pump load on it.
A.2. Performance analysis with MP DTC

The wind generation system dynamics are also evaluated utilizing the MP DTC technique [44]. The captured results shown in Figs. 42, 43, 44, 45 and 46 are representing the active and reactive powers, the $d$-$q$ stator current components and the PMSG torque, respectively. The MP DTC provides sufficient behavior through maintaining the actual values concise with their references. However, the accompanied ripples are obvious in the generator quantities. The MP DTC ripples are to some extent lower slightly than that of the MP DTC as it will be revealed in the comparison section.

The generated currents profile is also shown in Fig. 47, which shows that the current variation is emulating the variation in the generated power and in turn emulating the wind speed variation. Figs. 48, 49 and 50 illustrate the battery power, battery current and battery state of charge, respectively. Through these figures, it can be shown that the battery dynamics is well managed through adopting the PMS strategy which governs the BSS behavior.

In addition, the validity of the PMS is observed through the obtained dynamics of motor-pump unit. This is illustrated through Figs. 51, 52, 53 and 54 which show the pump power demand, the motor-pump torques, the power flow rate, and the water level inside the tank. From these illustration, it is realized that the PMS enable the pump operation at each instant happens that the water level decrease below the reference height (3.5 m); in addition the IM succeeded in tracking the reference torque provided by the PMS according to the pump requirement.

FIGURE 42. PMSG active power under MP DTC

FIGURE 43. PMSG reactive power under MP DTC

FIGURE 44. D- axis stator current under MP DTC

FIGURE 45. Q- axis stator current under MP DTC

FIGURE 46. PMSG torque under MP DTC

FIGURE 47. PMSG currents under MP DTC
A.3. Performance analysis with MP CC

The dynamics of the designed HPS is tested considering the MP CC technique [48] as a controller for the PMSG. The calculated values of active and reactive powers, \( d-q \) generator currents and the generator torque are shown respectively in Figs. 55, 56, 57, 58 and 59. In general, the controlled variables under the MP CC are exhibiting good tracking for their references, however the signal fluctuations are still remarkable. This fact is also noticed in the generated currents profile in Fig. 60. The validity of the BSS system control is also verified in this test; as illustrated in Figs. 61, 62 and 63 which show the battery power, battery current and the battery SOC. From these figures, it can be confirmed that the BSS control is effectively achieved. Also, the control performance of pump-motor unit is illustrated in Figs. 64, 65, 66 and 67 which respectively show the pump power, the torques of IM and pump, the water flow rate and the water level inside the tank. It can be noticed that the designed PMS has successfully managed the pumping system at each instant that the water level decreases below the predefined level.
FIGURE 56. PMSG reactive power using MP CC

FIGURE 57. D-axis stator current using MP CC

FIGURE 58. Q-axis stator current using MP CC

FIGURE 59. PMSG torque using MP CC

FIGURE 60. PMSG currents using MP CC

FIGURE 61. Battery power using MP CC

FIGURE 62. Battery current using MP CC

FIGURE 63. Battery SOC using MP CC

FIGURE 64. Pump demand power using MP CC

FIGURE 65. Motor-pump torques using MP CC
A.4. Performance analysis with proposed PVC

The dynamics of the HPS is also evaluated when considering the proposed PVC to manage the PMSG operation. The obtained results are illustrated in Figs. 68, 69, 70, 71 and 72 which show respectively the active and reactive powers, the $d$-$q$ current components and the encounter generator torque. By checking these figures and comparing it with their relevant values obtained using the MP DPC and MP DTC, it is obviously realized that the proposed control achieves better dynamics than the other predictive controllers. The ripples content is appropriately limited. The generator currents profile is also shown in Fig. 73, which exhibits less current harmonics in comparison with the current values under MP DPC and MP DTC. This fact is also approved in the captured values of the battery power and current as shown in Figs. 74 and 75. The battery SOC is also presented in Fig. 76. The dynamics of the motor-pump unit are also presented in Figs. 77, 78, 79 and 80 showing the pump power demand, the motor-pump torques, water flow rate and water height inside the tank. The adaptation of the water level is appropriately achieved thanks to the designed PMS which provides the IM with the optimal reference speed and torque to operate the pump.
A.4. Comparative performance analysis between the four predictive controllers

After analyzing the performance of each control technique in the previous sections, the current section presents the comparison between the four controllers. From the presented results, it is recognized that the proposed control achieves the lowest ripples. This is illustrated in Figs. 81, 82, 83, 84 and 85 which present the active and reactive powers, the d-q axes currents and the generator torque under the three controllers. Meanwhile, Figs. 86 and 87 illustrate the battery power and current for the four controllers, respectively. Moreover, the combined DC link voltage profile is shown in Fig. 88, from which it can be seen that the PVC provides less voltage fluctuation compared with the other three techniques.
The comparison between the four predictive controllers is also applied using the commutation as a measuring tool. This comparison is very vital for any predictive controller, as the predictive control is naturally time consuming. So reducing the computation time and consequently the computation burdens are vital need. Table 3 illustrates the performed commutations under the four controllers.

From this comparison, the validity of the proposed predictive control is approved through reducing the number of performed commutations which effectively help in limiting the switching losses, and provide a suitable computation environment to be used by the comparable microcontrollers.
An additional analysis for the current harmonics under the four control schemes is also carried out in order to visualize the advantage of the designed control respecting to the other three controllers. The briefed analytical statistics for the currents THD is presented in Table 4. In addition the graphical representation of the currents spectrum are also shown in Figs. 88, 69, 90 and 91 for the the four predictive control systems.

Table 3. Performed commutation

| Technique   | No of commutations |
|-------------|---------------------|
| MP DPC      | 253600              |
| MP DTC      | 296100              |
| MP CC       | 323700              |
| Proposed PVC| 70260               |

FIGURE 88. Current spectrum analysis under MP DPC

FIGURE 90. Current spectrum analysis under MP DTC

Table 4. Currents THD analysis

| Phase | MP DPC          | MP DTC          | MP CC           | Proposed          |
|-------|-----------------|-----------------|-----------------|-------------------|
| 'a'   | Essential (6.65465 A) THD (2.54 %) | Essential (6.38869 A) THD (2.06 %) | Essential (6.3842 A) THD (2.01 %) | Essential (6.67833 A) THD (1.46 %) |
| 'b'   | Essential (6.72207 A) THD (3.65 %) | Essential (6.48784 A) THD (3.33 %) | Essential (6.48222 A) THD (3.16 %) | Essential (6.75668 A) THD (2.47 %) |
| 'c'   | Essential (6.75742 A) THD (3.31 %) | Essential (6.46752 A) THD (3.25 %) | Essential (6.45439 A) THD (3.02 %) | Essential (6.59229 A) THD (2.60 %) |
From the figures of current spectrums, it is noticed that the designed control achieves the minimum THD, which helped effectively in improving the quality of the delivered power by the PMSG in comparison with the other predictive controllers used in the literature.

VII. CONCLUSION

The paper presented a comprehensive dynamic analysis for a renewable energy based water pumping system. The complete system components are constructed and described in details. The power system constituted of a wind turbine, PMSG, a water pumping system (WPS) and a battery storage system (BSS). The BSS is utilized to improve the power handling to the WPS system under weak wind production. To improve the dynamics of PMSG a new predictive control strategy is formulated which avoids the drawbacks of the traditional predictive control schemes. To confirm the superiority of the designed predictive control technique, extensive evaluation tests are carried out and presented in a comparison form with other three predictive controllers. A power management strategy (PMS) is developed to manage the power flow between the system units to ensure sufficient power delivery to the pumping system. Detailed tests are made to analyze the performance of PMS strategy. The results approved that the proposed PVC has the most effective performance in terms of
reduced ripples, low calculation capacity, structure simplicity and low current THD. The results also approved the validness of the designed PMS in balancing the power flow and stabilizing the DC bus voltage as well. Finally, the present study can be used as a base for future work in which additional energy sources (i.e. wave, fuel cell, solar) can be incorporated in favor of studying the system reliability while adopting different types of power management and control algorithms.

**APPENDIX**

**Table 4. PMSG and Turbine data**

| Variable          | Value       | Variable          | Value       |
|-------------------|-------------|-------------------|-------------|
| \( r \)           | 2 m         | \( p \)           | 4           |
| \( \mu_{\text{nom}} \) | 0.472       | \( R \)           | 820 mΩ      |
| \( P_{\text{nom}} \) | 3900 W       | \( p_{\text{r}} \) | 0.5 V/s     |
| \( V_{\text{nom}} \) | 10 m/s       | \( C \)           | 2200 µF     |
| \( \alpha \)       | 3.83        | \( U_{\text{dc}} \) | 550 V       |

**Table 5. Parameters of battery**

| Variable          | Value       | Variable          | Value       |
|-------------------|-------------|-------------------|-------------|
| \( R_c \)         | 0.00275 Ω   | \( L_{\text{nat}} \) | 0.03 H      |
| \( R_b \)         | 0.00375 Ω   | \( \text{Capacity} \) | 50 Ah       |
| \( R_b \)         | 0.00375 Ω   | \( U_{\text{bat,nom}} \) | 240 V       |
| \( C_s \)         | 883.7 mF    | \( \text{DOD} (\%) \) | 60 %        |
| \( C_c \)         | 82.1 mF     | \( \eta_{\text{bat}} \) | 85 %        |

**A. Design of PID controller for DC bus control**

The relationship between the voltage and current of the DC bus can be expressed in the \( s \) domain by

\[
\frac{u_{\text{dc}}(s)}{i_{\text{dc}}(s)} = \frac{1}{sC} 
\]

(72)

The PID operation can be described in the \( s \) domain by

\[
H(s) = K_{p,dc} + \frac{K_{i,dc}i_{\text{dc}}(s)}{s} + K_{d,dc}s 
\]

(73)

In addition, the relationship between the input DC link voltage error and output reference DC link current

\[
u_{\text{dc}}(s) - U_{\text{dc}}(s) \ast \left( K_{p,dc}s + K_{i,dc} + K_{d,dc}s^2 \right) = si_{\text{dc}}(s) 
\]

(74)

By dividing all sides on \( i_{\text{dc}}(s) \) and after some manipulations, it results

\[
\frac{u_{\text{dc}}(s)}{i_{\text{dc}}(s)} = \frac{(K_{d,dc}s + C) \ast p + K_{p,dc}s + K_{d,dc}}{K_{d,dc}(s + C) + K_{p,dc}s + K_{i,dc}s} 
\]

(75)

In order to have stable controller dynamics, the characteristic equation of the function (75) must have negative real roots, and this can be achieved via equating the denominator of (75) with zero as follows

\[
K_{d,dc}C^3 + K_{p,dc}Cs^2 + K_{i,dc}Cs = 0 
\]

(76)

Alternatively, the open loop (OL) dynamics for a third order system can be represented by the following transfer function [57]

\[
H_o(s) = \frac{Y(s+z)}{s^2(s+p)} 
\]

(77)

where \( p \) and \( z \) represent the pole and zero of the OL system, and \( Y \) is the OL gain and it equals the system natural frequency \( \omega_n \).

Both \( p \) and \( z \) can be defined in terms of the system natural frequency \( \omega_n \) and the damping factor \( \zeta \) as following

\[
p = 2\zeta\omega_n \quad \text{and} \quad z = \frac{4\zeta^2}{\omega_n} 
\]

(78)

In a similar to (77), the closed loop (CL) dynamics of a third order system can be described by the following transfer function

\[
H_c(s) = \frac{H_o(s)}{1+H_o(s)} = \frac{\omega_n(s+z)}{s^3+pzs^2+\omega_nzs+s\omega_n} 
\]

(79)

The denominator of (79) represents the characteristic equation which emulates the desired dynamics for a third order system. In order to have a stable operation, the roots of this function must be with negative real values, and accordingly the following condition should be fulfilled

\[
s^3 + pzs^2 + \omega_nzs + \omega_nz = 0 
\]

(80)

Now, by comparing the relevant terms of (76) and (80), the parameters of PID controller can be determined as following

\[
K_{p,dc} = \frac{3}{C}, \quad K_{i,dc} = \frac{2\zeta\omega_n}{C}, \quad K_{d,dc} = \frac{\omega_n}{C} 
\]

(81)

**B. Design of PID controller for BSS control**

The PID used for the BSS is illustrated in a section view in Fig. 92, where \( x \) represents the output of the PID controller and it can be expressed in the \( s \) domain by

\[
x(s) = U_{\text{bat}}(s) - U_{\text{m,bat}}(s) = U_{\text{bat}}(s) - m\star u_{\text{dc}}(s) 
\]

(82)
FIGURE 76. BSS control loop

From the voltage balance on the battery terminals, the voltage difference between $U_{bat}$ and $U_{n,bat}$ represents the voltage across the inductor $I_{bat}$ and consequently (82) can be represented assuming zero initial inductor current by

$$x(s) = sL_{bat}I_{bat}(s)$$ (83)

Using (83), the input-output dynamic of the PID controller of the BSS can be then expressed by

$$(I_{bat}(s) - I_{bat}^*(s)) \times \left( K_{p,B} + \frac{K_{i,B}}{s} + K_{d,B}s \right) = sL_{bat}I_{bat}(s)$$ (84)

By dividing all parts of (84) on $I_{bat}^*(s)$ and by performing some manipulations, the transfer function which governs the dynamics of the designed PID can be expressed by

$$I_{bat}(s) = \frac{K_{d,B}s^2 + K_{p,B}s + K_{i,B}}{(K_{d,B} + K_{p,B}s + K_{i,B})(K_{d,B} + K_{p,B}s + K_{i,B})}$$ (85)

To have stable dynamic operation, the characteristic equation represented by the denominator of (85) should be with negative real roots, consequently the following condition should be fulfilled

$$(K_{d,B} + L_{bat})s^2 + K_{p,B}s + K_{i,B} = 0$$ (86)

On the other hand, the characteristic equation of the second order dynamic system can be defined by

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$$ (87)

Now, by comparing the terms of (86) and (87), the PID parameters are calculated as following

$$K_{p,B} = 2\zeta\omega_n, \quad K_{i,B} = \omega_n^2, \quad K_{d,B} = 1 - L_{bat}$$ (88)

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