ESO-based FTC strategy via dual-loop compensations for 5-phase PMSG integrated tidal applications

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Abstract Using multiphase permanent magnet synchronous generators (PMSG) is able to strengthen whole reliabilities of the tidal stream energy systems. Even so, advanced fault-tolerant control designs are also needed for a further enhancement of multiphase PMSG integrated tidal stream turbine under harsh sea water environments. Thus, extended state observers are used to develop a fault-tolerant control strategy towards a trapezoidal five-phase PMSG incorporated tidal stream application. This FTC strategy considers open circuit of a phase and a switch in the five-phase PMSG and its connected converter. To attenuate influences due to these faults, a dual-loop compensation mechanism is performed via extended state observers. System adaptation to swell effects of the tidal stream and feasibility of the proposed FTC strategy are verified through a 1.5 MW simulation setup.

key words: Tidal stream applications, five-phase PMSG, fault-tolerant control, dual-loop compensation

Classification: Energy harvesting devices, circuits and modules

1. Introduction

Tidal stream power becomes attractive with regards of its availabilities [1, 2]. Multiphase permanent magnet synchronous generator (PMSG) integrated tidal stream turbines is a promising way to harvest energies with a high fault tolerance [3]. However, the tidal stream turbines will continuously suffer from the erosions due to the ocean creatures and salinity, whose further studies on the dual-loop compensations under faulty conditions are needed for a further enhancement of multiphase PMSG incorporated tidal stream application. This FTC strategy considers open circuit of a phase and a switch in the five-phase PMSG and its connected converter. To attenuate influences due to these faults, a dual-loop compensation mechanism is performed via extended state observers. System adaptation to swell effects of the tidal stream and feasibility of the proposed FTC strategy are verified through a 1.5 MW simulation setup.

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2. System modelling

Fig. 1 indicates synoptic system diagram. It consists of tidal stream input, turbine, a 5-phase PMSG, AC-DC-AC converters, a control system and a transformer to deliver powers to grid networks.

![Fig. 1. Five-phase PMSG based tidal stream full power conversion chain.](image)

2.1 Tidal stream source

To reach more realistic tidal stream model, swell effects [25] should be considered, which are formulated mainly by winds imposing upon the surface of sea water. This phenomenon can be clarified as shown in Fig. 2.

![Fig. 2. Swell effects for a tidal stream turbine.](image)

In general, swell effects can be characterized as Eq. (1) below [26].

\[
\nu_{tides}(t) = \nu_{tides0} + \sum_h \frac{2\pi A_h}{T_h} \cos \left(2\pi \frac{z + d}{L_h} \right) \cos \left(2\pi \left(\frac{t}{T_h} - \frac{x}{L_h} + \phi_h \right) \right) \frac{\sinh \left(2\pi \frac{d}{L_h} \right)}{ \sinh \left(2\pi \frac{d}{L_h} \right)},
\]

where the first term in the right side of above equation represents the theoretical value of the tidal stream velocities. The second term approximates the swell signal with different harmonics. The harmonic order of the tidal stream velocities is defined as “h”. \(x\) and \(z\) are respectively the sampling points in horizontal and vertical directions in Eq. (1). \(d\) means the installed depth under sea water. \(A_h, T_h, L_h\) and \(\phi_h\) are respectively amplitude, magnitude, period, length and initial phase angles of the \(h\)th harmonic component. Thus, a simulated example of tidal stream velocity is given as shown in Fig. 3(a) under the swell effects when \(\nu_{tides}\) operates at 2.55 m/s, whose spectrum is presented in Fig. 3(b).

where the swell mainly oscillates around 0.065 Hz. It is clear to observe that the disturbances due to swell effects can be coped as an additive component, which has impacts on system operations. The designed control strategy should adapt to this speed fluctuations.

![Fig. 3. Analysis of tidal stream under swell effects.](image)

2.2 Turbine model

Eq. (2) illustrates the harvesting kinetic energy from the tidal stream through a horizontal axis turbine.

\[
P_m = \frac{1}{2} m \nu_{tides}^2 C_p,
\]

where \(P_m\) is the mechanical power of turbine, \(m\) means the density of water, \(\nu_{tides}\) is tidal stream velocity, \(r\) is the radius of turbine blade, \(m\) is the weight of water through the swept area of turbine under unit of time. \(C_p\) is the power coefficient function related to tip speed ratio \(\lambda\) and pitch angle, where the expression of \(\lambda\) is given by Eq. (3).

\[
\lambda = \omega_m r / \nu_{tides}.
\]

It should be noted that this paper concentrates on the duration of maximum power tracking algorithm (MPPT) where the pitch angle is absent.

2.3 Trapezoidal five-phase PMSG model

The saturation, eddy currents and iron loss are negligible for a five phase PMSG with star-windings here. According to equivalent machine set theory [27], the five-phase PMSG can be decomposed as primary, secondary
and homopolar machines with magnetic decoupling. In this paper, the 5-phase PMSG contains two harmonics: the fundamental and the third harmonic, which formulate the trapezoidal back-EMFs. Under Park’s frames, voltage equation of the generator is given by Eq. (4).

\[
\begin{align*}
\dot{u}_{pd} &= e_{pd} - R_s i_{pd} - L_{pr} \frac{di_{pd}}{dt} + \omega_e L_{pr} i_{pq} \\
\dot{u}_{pq} &= e_{pq} - R_s i_{pq} - L_{pr} \frac{di_{pq}}{dt} - \omega_e L_{pr} i_{pd} \\
\dot{u}_{sd} &= e_{sd} - R_s i_{sd} - L_{se} \frac{di_{sd}}{dt} + 3\omega_e L_{se} i_{sq} \\
\dot{u}_{sq} &= e_{sq} - R_s i_{sq} - L_{se} \frac{di_{sq}}{dt} - 3\omega_e L_{se} i_{sd} \\
\dot{u}_{0dq} &= e_{0dq} - R_s i_{0dq} - L_{0dq} \frac{di_{0dq}}{dt}
\end{align*}
\]

here \(L_{pr} = L_s + \frac{\sqrt{5} - 1}{2} M_1 - \frac{\sqrt{5} + 1}{2} M_2, L_{se} = L_s + \frac{\sqrt{5} + 1}{2} M_1 + \frac{\sqrt{5} - 1}{2} M_2\) and \(L_{0dq} = L_s + 2M_1 + 2M_2\) are the equivalent inductance for primary, secondary and homopolar machines, respectively. Electromagnetic torque and mechanical equation are described by Eq. (5) and Eq. (6).

\[
T_{em} = -\left(i_{pd} e_{pd} + i_{pq} e_{pq} + i_{sd} e_{sd} + i_{sq} e_{sq} + i_{0dq} e_{0dq}\right) \frac{\omega_m}{\omega_m} \frac{d\omega_m}{dt} = T_m - T_{em} - f\omega_m.
\]

where \(\omega_m = \omega_m / p\) is the mechanical speed, \(p\) represents number of pole pairs, \(J, f, T_{em}\) and \(T_m\) are respectively inertia of generator, friction coefficient, electromagnetic torque and mechanical torque.

3. Design of fault-tolerant control strategy

3.1 Control references

This paper utilizes an optimal TSR-based MPPT [28], which provides desired speed and mechanical torque references as Eq. (7) below.

\[
\omega_{m,ref} = \frac{\nu_{tides}}{r} \lambda_{opt}, T_{m,ref} = \frac{\rho r^5 C \tilde{P}_{max}}{2 \lambda_{opt}^3} \omega_m^2.
\]

To minimize copper losses [29, 30], \(q\)-axis current references can be expressed by Eq. (8) and the references for \(d\)-axis are forced into zeros.

\[
i_{pq,ref} = -\frac{T_{em,ref}}{\sqrt{\frac{5}{2} p \Phi_1 (1 + X^2_\Phi)}}, i_{sq,ref} = X_\Phi i_{pq,ref}.
\]

where \(\Phi_1\) and \(\Phi_2\) are respectively the first and third harmonics of air gap fluxes of the five-phase PMSG. The relative ratio between primary and secondary machines is \(X_\Phi = 3\Phi_2 / \Phi_1\). If the mechanical speed control loop can well adapt to the swell effects, the referred can be summarized as below according to Eq. (4,7 and 8).

\[
T_{em,ref} \approx \frac{\rho r^5 C \tilde{P}_{max}}{2 \lambda_{opt}^3} \left(\frac{\lambda_{opt}}{r} \nu_{tides} - \omega_m\right)^2 - f \left(\frac{\lambda_{opt}}{r} \nu_{tides} - \omega_m\right) - J \left(\frac{\lambda_{opt}}{r} \nu_{tides} - \omega_m\right)\]

From the above equation, it can be found that the reference torque can be characterized with a function of \(\nu_{tides}\) and \(\omega_m\). Under a satisfactory control strategy along the swell effects, the inner current loops will be interfered by speed fluctuations from the outer loop. Inversely, the measured current suffers from the distortions due to the open circuit faults, which will propagate to the outer loop as well under the feedback paths. This is the reason why compensations are placed in dual loops to eliminate the interactions between the dual loops as much as possible with more control degrees of freedom.

3.2 Observer designs for five-phase PMSG systems

According to Eq. (6) and Eq. (9), the dynamic expressions with augmented fault and swell effects are given by

\[
\begin{align*}
\dot{i}_{pd} &= \frac{R_s}{L_{pr}} i_{pd} + \omega_e i_{pq} + f_{pd} - \frac{u_{pd}}{L_{pr}} \\
\dot{i}_{pq} &= \frac{R_s}{L_{pr}} i_{pq} - \omega_e i_{pd} + \sqrt{\frac{5}{2}} \frac{\omega_e \Phi_1}{L_{pr}} + f_{pq} - \frac{u_{pq}}{L_{pr}} \\
\dot{i}_{sd} &= \frac{R_s}{L_{pr}} i_{sd} + 3\omega_e i_{sq} + f_{sd} - \frac{u_{sd}}{L_{se}} \\
\dot{i}_{sq} &= \frac{R_s}{L_{pr}} i_{sq} - 3\omega_e i_{sd} + 3\sqrt{\frac{5}{2}} \frac{\omega_e \Phi_1}{L_{se}} + f_{sq} - \frac{u_{sq}}{L_{se}} \\
\dot{\omega}_m &= -f\omega_m / J, T_{m,ref} - T_{em} / J + f_\omega.
\end{align*}
\]

Define state terms \(\omega_m, i_{pq}, i_{sd}\) and \(i_{sq}\) as \(x_\omega, x_{pd}, x_{pq}, x_{sd}\) and \(x_{sq}\), respectively. Denote fault terms \(f_\omega, f_{pd}, f_{pq}, f_{sd}\) and \(f_{sq}\) as \(x_\omega, x_{pd}, x_{pq}, x_{sd}\) and \(x_{sq}\), respectively. It is obvious that system described in Eq. (4) has full rank and is observable. The following observers can be thus established as Eq. (11) based on ESO.

\[
\begin{align*}
\dot{x}_\omega_1 &= \beta_\omega_1 (x_\omega_1 - x_\omega_1) - f \dot{x}_\omega_1 / J \\
\dot{x}_\omega_2 &= \alpha_\omega_1 \dot{x}_\omega_2 + \beta_\omega_2 (x_\omega_1 - x_\omega_1) \\
\dot{x}_{pd1} &= \beta_{pd1} (x_{pd1} - x_{pd1}) - \frac{R_s}{L_{pr}} \dot{x}_{pd1} + x_{pd2} - \frac{u_{pd}}{L_{pr}} \\
\dot{x}_{pd2} &= \alpha_{pd1} \dot{x}_{pd2} + \beta_{pd2} (x_{pd1} - x_{pd1}) \\
\dot{x}_{pq1} &= \beta_{pq1} (x_{pq1} - x_{pq1}) - \frac{R_s}{L_{pr}} \dot{x}_{pq1} + x_{pq2} - \frac{u_{pq}}{L_{pr}} \\
\dot{x}_{pq2} &= \alpha_{pq1} \dot{x}_{pq2} + \beta_{pq2} (x_{pq1} - x_{pq1})
\end{align*}
\]

(11)

where the symbols related to \(\alpha, \beta\) with corresponding subscripts are the observer gains, whose parameter setting should ensure dynamics of estimated error asymptotically stable. Eq. (11) only gives the speed loop and current loop in terms of the primary machine. The current compensations for the secondary machine are consistent to the primary one. Then the control law can be reconfigured by the augmented estimates in order
to compensate the perturbed terms in Eq. (10). The global control diagram is illustrated as Fig. 5. Particularly, the decoupling terms in Park’s frames are regarded as compensated disturbances.

4. Simulation analysis

In order to test the feasibility of the proposed FTC strategy, a Simscape-based 1.5MW tidal stream energy simulation setup using a trapezoidal five-phase PMSG is established by MATLAB/SIMULINK. Tidal stream profiles will be imported performed as the profiles described in Fig. 3(a). As the marks in the Fig. 5, composite controllers are reconfigured by using the compensation information from the built observers respectively in speed and current loops. The main parameters are listed in Table I.

| Table I. Main parameters used in simulation setup |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( J \) | Total inertia | 1.3144 \& 10^6 kg m^2 |
| \( f \) | Friction coefficient | 0.01 |
| \( P_{\text{dc}} \) | Generator rated power | 1.5 MW |
| \( V_{\text{dc}} \) | DC-bus voltage | 1700 V |
| \( \omega_{\text{m}} \) | Rotor rated speed | 2.618 rad/s |
| \( p \) | Pole pair number | 120 |
| \( \phi_1 \) | Primary machine magnet flux | 2.438 Wb |
| \( \phi_2 \) | Secondary machine magnet flux | 0.082 Wb |
| \( R_e \) | Generator stator resistance | 0.0081 \& |
| \( L_{\text{pr}} \) | Primary machine reactance | 1.2 mH |
| \( L_{\text{sec}} \) | Secondary machine reactance | 0.88 mH |
| Observer gains | Related to \( \alpha \), related to \( \beta \) | 50, 20000 |

4.1 Performance in healthy operation modes

A real tidal stream velocity profile with during 70 seconds is adopted in order to test the adaptation to swell effects. It can be observed that the well-controlled system can track the tidal stream velocity with swell effects, as well as produce desired five-phase current and a stable DC bus voltage, which provides a precondition for the remainder validations. The DC bus voltage is constrained with around 2% thanks to the grid side controllers. For ease of descriptions, four FTC schemes are defined as below. Note that “no compensation” is treated as a special FTC scheme here.

1) Scheme-1: no compensation;
2) Scheme-2: compensation in speed loop;
3) Scheme-3: compensation in current loop;
4) Scheme-4: compensation in dual loops.

4.2 Post-fault tolerant performance

In order to investigate the fault-tolerance as the open circuit faults happen, a constant tidal stream profile is more preferred since the process of fault-tolerance is emergent in practical occasions relative to the low-speed process of the turbine, even with the swell effects. As shown in Fig. 6(a), the upper switch in leg ‘a’ is open at 0.1s in Figure 1. Figure 6(b) shows the open phase fault at phase ‘a’. The different compensation schemes are put into use before the fault occurrences in order to compare their fault tolerance in faulty operation modes. From Fig. 6(a), speed fluctuations will be suppressed most by scheme-3 while scheme-4 will contribute to smallest torque ripples benefit from the hybrid mechanism. Affected by the structural fault, scheme-2 has some enhancement but hard to satisfy the requirements in post-fault operation modes. It can be seen that scheme-3 is a necessary selection here to assist the speed loop compensations.

In Figure 7(b), the fault-tolerant performance keeps in line with the previous analysis while there are signifi-
cant improvements as a more severe open circuit (phase ‘a’) occurs at 0.1s. It should be known that uncompensated phase current is presented as the first sub-figures in Fig. 6(a) and (b) to indicate faulty moments. Besides, two performance indicators of torque ripples and speed fluctuations are given in order to evaluate post-fault operations by the different FTC schemes, which are expressed as Eq. (12) and Eq. (13). Table II intuitively summarizes the comparison results via these two performance indicators under the switch open case at $S_1$ and phase open case at phase ‘a’. Obviously, all of the compensation schemes (scheme-2, 3, 4) are able to suppress the speed fluctuations and torque ripples comparing to no compensation scheme. In detail, the hybrid scheme performs best not only the speed fluctuations but also the torque ripples. Relative to scheme-1, scheme-4 can reduce 60% and 65% speed fluctuations respectively to the switch and phase open cases. As for torque ripples, scheme-4 can also obtain about 46% and 62% attenuations comparing with the no compensation scheme.

$$T_{em\_ripple} = \frac{\max(T_{em}) - \min(T_{em})}{\text{Average}(T_{em})}$$

$$\omega_{m\_fluc} = \frac{\max(\omega_m) - \min(\omega_m)}{\text{Average}(\omega_m)}$$

Table II. Main parameters used in simulation setup

| Fault type           | FTC scheme | speed fluctuation | Torque ripples |
|----------------------|------------|-------------------|----------------|
| Open circuit of $S_1$| Scheme-1   | 0.0065            | 26.593         |
|                      | Scheme-2   | 0.0071            | 22.859         |
|                      | Scheme-3   | 0.0024            | 16.287         |
|                      | Scheme-4   | 0.0026            | 14.236         |
|                      | Scheme-1   | 0.0129            | 59.051         |
|                      | Scheme-2   | 0.0098            | 37.769         |
|                      | Scheme-3   | 0.0054            | 35.437         |
|                      | Scheme-4   | 0.0045            | 22.136         |

5. Conclusion

An FTC strategy by ESO is developed in this paper via dual-loop compensation mechanism. The basic control strategy against swell effects of tidal streams is discussed at first through an optimal tip speed ratio based MPPT approach, a dual-loop vector control strategy with minimized copper losses. Under this guaranteed control system, a simulation setup with full power conversion chain is performed with a real-scale turbine model. Open circuit faults of phase and switch are investigated in the trapezoidal five-phase PMSG and its serried converter. By comparative studies of compensations in different loops, the test result show that the developed dual-loop compensation is able to increasingly suppress the speed fluctuations and torque ripples, which enhance the availability in post-fault operations of tidal stream turbine systems. In the next stage, the developed strategy will be considered for an actual test to a tidal stream turbine under the sea water.

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