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Self-Synchronous Control of Doubly-Fed Linear Generators for Ocean Wave Energy Applications

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***Abstract*—A versatile doubly-fed linear generator was recently presented for application in the point absorber ocean wave energy converter (WEC). Although the machine may be operated as a classical synchronous machine, or as a singly- or doubly-fed induction machine, a self-synchronous approach to operating the machine is found to be attractive in low speed, high force applications. This is particularly beneficial for WECs since operating conditions alternate between positive and negative velocity at low speeds with high force. This characteristic lends itself to the proposed unique control approach. This paper develops the analytical concepts behind this controller as well as detailed simulation results.**

Keywords-ocean wave energy conversion; doubly-fed linear machine control; alternative energy conversion

I. INTRODUCTION

In wave energy converter (WEC) applications, direct drive power take-off is less mechanically complex than hydraulic- or pneumatic-based systems and thus has the opportunity for superior performance and increased efficiency. Further efficiency gains may be achieved by coupling the direct drive with a proper control scheme. Although permanent magnet and reluctance machines of various types have been considered for WEC applications [4-8], a versatile doubly-fed machine was recently presented as an alternative approach [1]. This paper presents a self-synchronous controller for maximum energy extraction from such a doubly-fed linear machine. Fig. 1 illustrates the sketch of a prototype machine module and is used as a case study for developing the proposed controller.

A large body of work is dedicated to doubly-fed induction machine control, aimed mainly at wind generators. Several control techniques exist with goals such as constant frequency, torque control, and active/reactive power control [2], [3]. Most of these control methods make use of the field oriented control concept whereby the machine fluxes are manipulated for a desired outcome.

The difference between wind and ocean wave applications for doubly-fed machines is multifaceted. The main difference being that a wind generator operates within a narrow speed range whereas the working speed range for a wave generator is much larger, ranging from zero speed to maximum speed. In this way, the wave energy generator cannot be expected to maintain a single output frequency. Thus the control approach requires a fresh outlook developed further in this paper. The following section presents the overall system control approach, followed by a presentation of the proposed self-synchronous power control topology. A block diagram and control approach for the self-synchronous topology is presented in Section III, along with analytical results. Computer simulation waveforms and details of the machine results are presented in Section IV.

II. SELF SYNCHRONOUS MACHINE TOPOLOGY

A. *Relationship between Force and Velocity*

In WEC applications, machine velocity varies cyclically, which may be approximated to be sinusoidal. To maximize power harvest, the machine force should be maintained proportional to velocity since the product of force and velocity represent the power harvested. If the machine's force does not track velocity, a 'reactive' force (motoring power) will be developed. Thus, the controller force command value should follow the relationship in (1).

$$F^* = k\,v_{trans}\,. \tag{1}$$

B. *Electrical Frequency and Wiring Requirements*

The premise behind the self-synchronous machine control strategy developed in this paper is that both the stator and translator operate at the same electrical frequency but with opposite polarity.

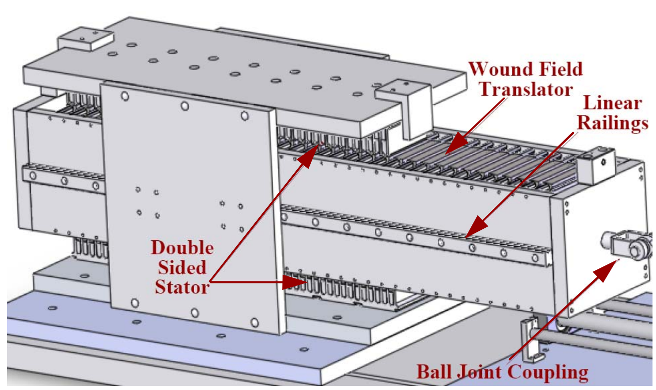

Figure 1. Hybrid Flux Linear Machine as developed in [1]

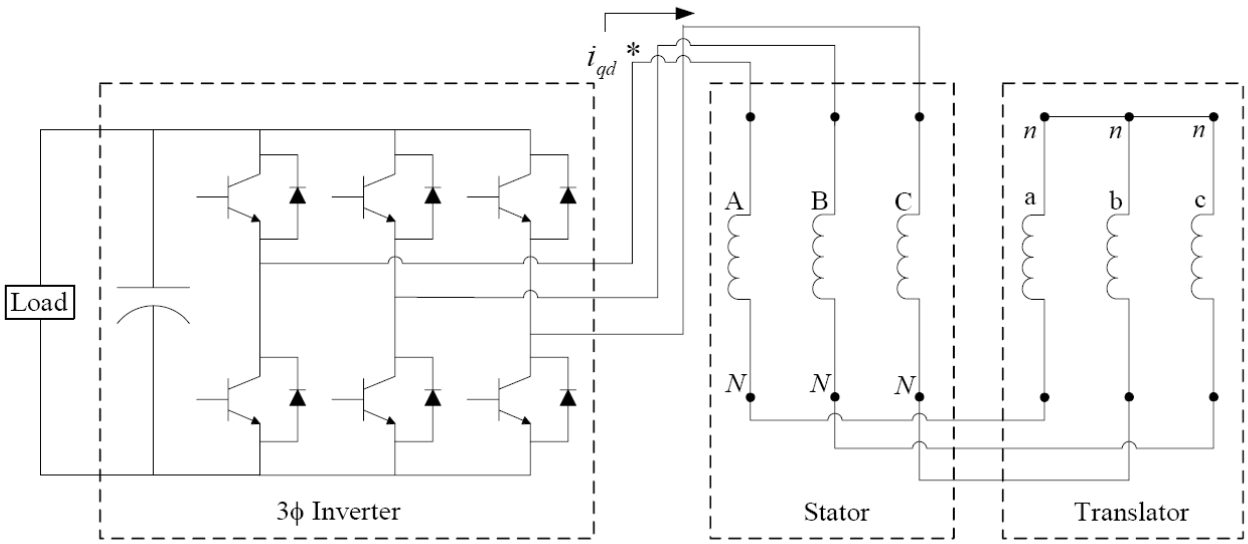

Figure 2. Power Circuit Interconnections for the Proposed Self-Synchronous Controller for the Doubly Fed Induction Generator

This arrangement leads to synchronous operation when the electrical speed of the physical carriage is twice that of the stator, which causes the frequency of the stator and translator fields in the airgap to match. Table I shows various velocity components under this mode of operation.

Furthermore, the doubly-fed linear machine's translator cables can be accessed directly via a flexible cable rather than through slip rings. Since the translator currents can be sensed and used to directly calculate the translator fields, a direct field oriented control method may be employed. This setup also allows for the special winding connections needed to implement the self-synchronous controller presented in this paper. The primary benefit of using this wiring arrangement is its ability to develop large forces at low speeds much like a series wound DC machine. This property is well-suited for WEC applications since their operating speeds are low and require large reaction forces. To ensure self-synchronism as presented in Table I (i.e. the electrical frequency of the stator and the translator are opposite each other), the terminals of the stator windings are connected to the terminals of the translator windings as depicted in Fig. 2. In this way, if the stator experiences positive sequence current, the translator will experience negative sequence current and vice-versa.

TABLE I. DOUBLY-FED LINEAR MACHINE CONTROL: ELECTRICAL FREQUENCY OF STATOR, TRANSLATOR, AND THE PHYSICAL CARRIAGE

	Stator	**Physical Carriage**	**Translator**
Electrical Frequency:	ω	2ω	ω

III. SELF-SYNCHRONOUS CONTROL APPROACH

A. Reference Frame

The controller reference frame is tied to the synchronous excitation frequency as defined in Table I and in equation (2).

$$\omega_{ref} = \omega_e = \frac{\pi}{2\tau_{s,pole}} v_{mech} . \tag{2}$$

B. Analytical Machine Model

Under the proposed winding connections, equations (3) and (4) express the relationship between the stator and translator current and voltage respectively, where '†' denotes the complex conjugate and the superscript 'e' denotes the synchronous reference frame.

$$i^e_{qds} = i^{e\,\dagger}_{qdr} . \tag{3}$$

$$v^e_{terminal} = v^e_{qds} + v^{e\,\dagger}_{qdr} . \tag{4}$$

By substituting the relations in (2)-(4) into the dq-axis induction machine equations [9], the self-synchronous machine and force equations in (5) and (6) emerge, where p represents the Laplace operator and the other variables follow standard notation listed in Table II.

$$F = \frac{3\pi L_m}{\tau_{s,pole}} i^e_q i^e_d . \tag{5}$$

$$\begin{bmatrix} v^e_{q,terminal} \\ v^e_{d,terminal} \end{bmatrix} = \begin{bmatrix} (r_r + r_s) + p(L_r + L_s + 2L_m) & \omega_e (L_r + L_s - 2L_m) \\ -\omega_e (L_r + L_s + 2L_m) & (r_r + r_s) + p(L_r + L_s - 2L_m) \end{bmatrix} \begin{bmatrix} i^e_{q,terminal} \\ i^e_{d,terminal} \end{bmatrix} . \tag{6}$$

C. *Controller Parameters: Voltage Angle and Magnitude*

In this application, control of both the stator and translator is limited to the terminal excitation. It is apparent from (6) that manipulating the terminal voltage angle and magnitude is the key to controlling current and thus the reactive force. The following subsections use the machine parameters presented in Table II for analysis.

TABLE II. HYBRID FLUX MACHINE PARAMETERS FROM [1]

Parameter	Symbol	Value	Units
Rated Line-Line Voltage	$V_{RMS,LL}$	230	(V_{RMS})
Rated RMS Current	I_{RMS}	14.38	(A)
Number of Poles	P	8	(-)
Stator Resistance	r_s	2.8	(Ω)
Translator Resistance	r_r	2.4	(Ω)
Stator Inductance	L_s	0.13	(mH)
Translator Inductance	L_r	0.15	(mH)
Magnetizing Inductance	L_m	0.1	(mH)
Stator Pole Pitch	$\tau_{s,pole}$	0.078	(m)
Active (Airgap) Area	$A_{airgrap}$	0.1248	(m^2)
Stroke Length	l_{stroke}	0.3	(m)

1) *Effect of Voltage Angle on Steady State Output*

Two methods of analysis are employed to study the effect of voltage angle on steady state output: 1) constant voltage magnitude and 2) constant V/Hz. The following two subsections describe these in relation to force production.

a) *Constant Voltage Magnitude*

Fig. 3 shows steady state force production over a range of voltage angles for discrete translator velocities. It should be noted that when velocity is positive, negative forces are in the generating regime and vice versa. It should also be noted that the forces associated with corresponding negative and positive velocities have odd symmetry about 180°, i.e. $F(v = -0.1$ m/s, $\theta_v > 180°) = -F(v = 0.1$ m/s, $\theta_v < 180°)$. As indicated by (5) and (6) and shown here, force production varies linearly with speed.

As mentioned previously, this type of controller yields large forces at low speeds. The best way to illustrate this is to examine the force density versus translator speed. It is evident from Fig. 4 that the maximum generating force is largest at lower speeds.

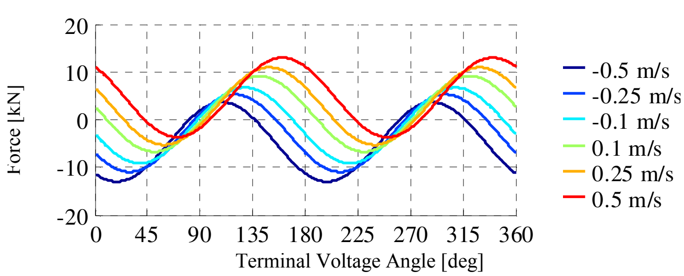

Figure 3. Steady State Force vs. Voltage Angle for Multiple Translator Velocities when Terminal Voltage Magnitude is held Constant

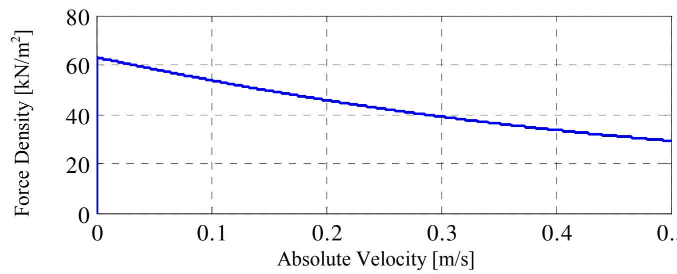

Figure 4. Steady State Maximum *Generating* Force Density vs. Velocity

b) *Constant V/Hz*

Constant V/Hz is well suited for variable speed applications such as this WEC application. Fig. 5 presents the steady state constant V/Hz force production and dq-currents over a range of voltage angles for discrete translator velocities. These values are used to determine the command trajectory as presented in subsection 2).

2) *Constant V/Hz Maximum Force Command Trajectory*

When using the constant V/Hz control approach, the maximum generating force is closely proportional to velocity as depicted in Fig. 6. Therefore the condition for maximum power capture as defined in (1) is satisfied. This maximum generating force trajectory is used as a command trajectory for the self-synchronous controller. In this way, the operating conditions (v_{qd} and i_{qd}) associated with each velocity's maximum force operating point are the command values at that velocity.

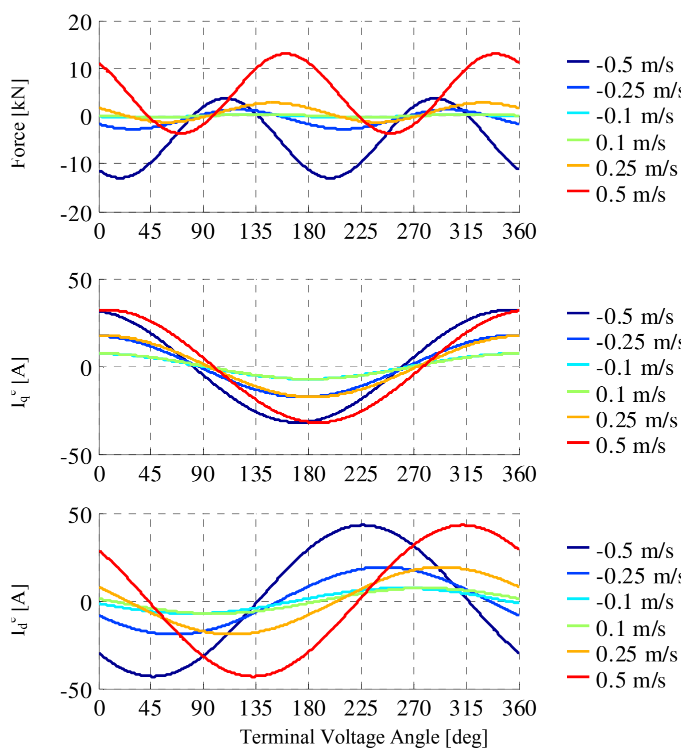

Figure 5. Steady State Force, Voltage, and Current vs. Voltage Angle for Multiple Translator Velocities when Terminal V/Hz is held Constant

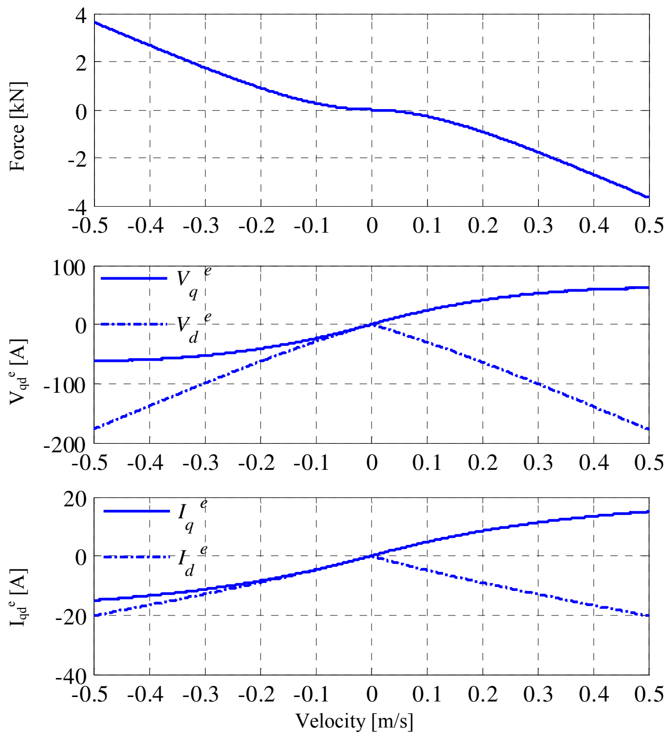

Figure 6. Constant V/Hz Maximum Power Command Trajectory

Characteristics of the constant V/Hz self-synchronous control scheme include:

1) The voltage and current decay to zero at zero velocity.

2) As the velocity transitions between positive and negative, both the stator and translator flux changes polarity to maintain a leading translator flux. This premise is taken in field oriented control where the maximum power condition occurs when the translator flux leads the stator flux by 90°.

3) The q-axis voltage and current are responsible for changing flux polarity.

D. Controller Architecture

Fig. 7 shows the self-synchronous controller architecture. A look-up table is used to produce commanded synchronous frame voltage and current. These command values are the maximum force operating points defined in Fig. 6.

The command values are fed into a PI controller where error in the current is zeroed and the command voltage is fed forward. This overcomes the effect of the machine inductances to a small extent. More sophisticated current regulators include various decoupling techniques to overcome the cross-coupling between different variables, leading to increased performance levels.

IV. SIMULATION RESULTS

In order to verify the operation of the proposed approach, Matlab-Simulink is used to simulate the dynamic effects of this machine and its controller. Fig. 8 shows the waveforms obtained from the simulation of the controller and the machine to a candidate sinusoidal variation in velocity. While the translator velocity, command force, real and reactive power waveforms are plotted on the right panels of the figure, the left panel illustrates the variation of d and q components of voltages and currents respectively. The fidelity of the system in following the command trajectories are evident from the waveforms.

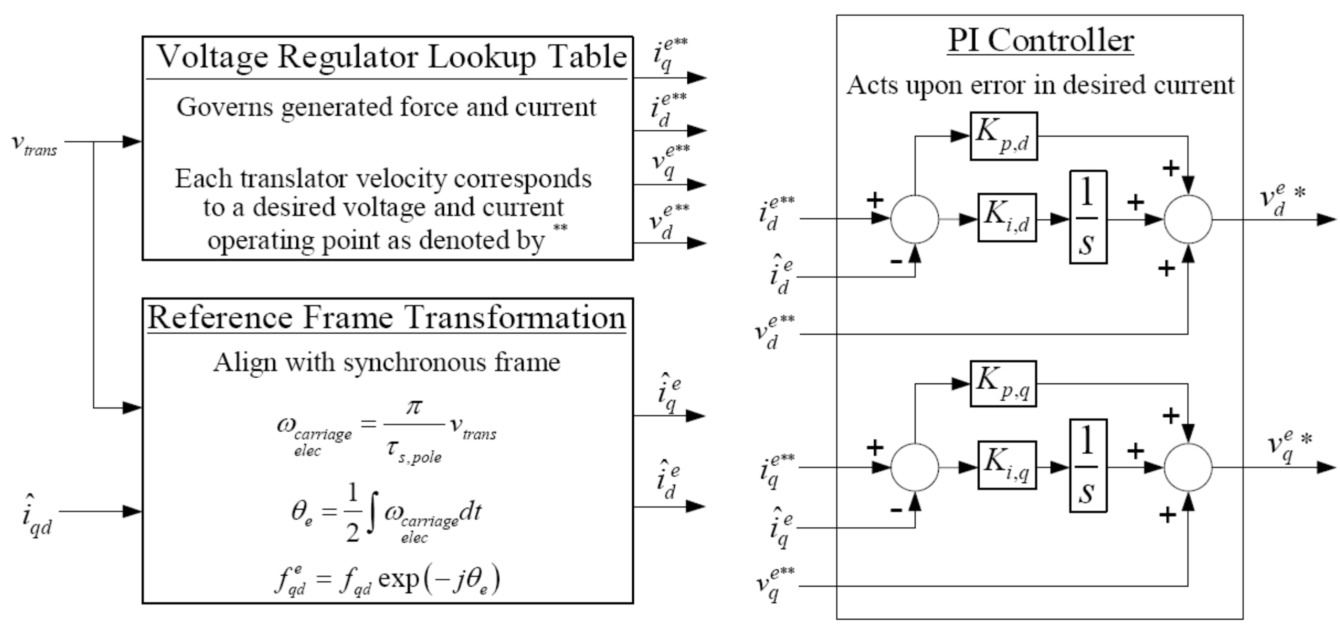

Figure 7. Self-Synchronous Maximum Power Controller Block Diagram

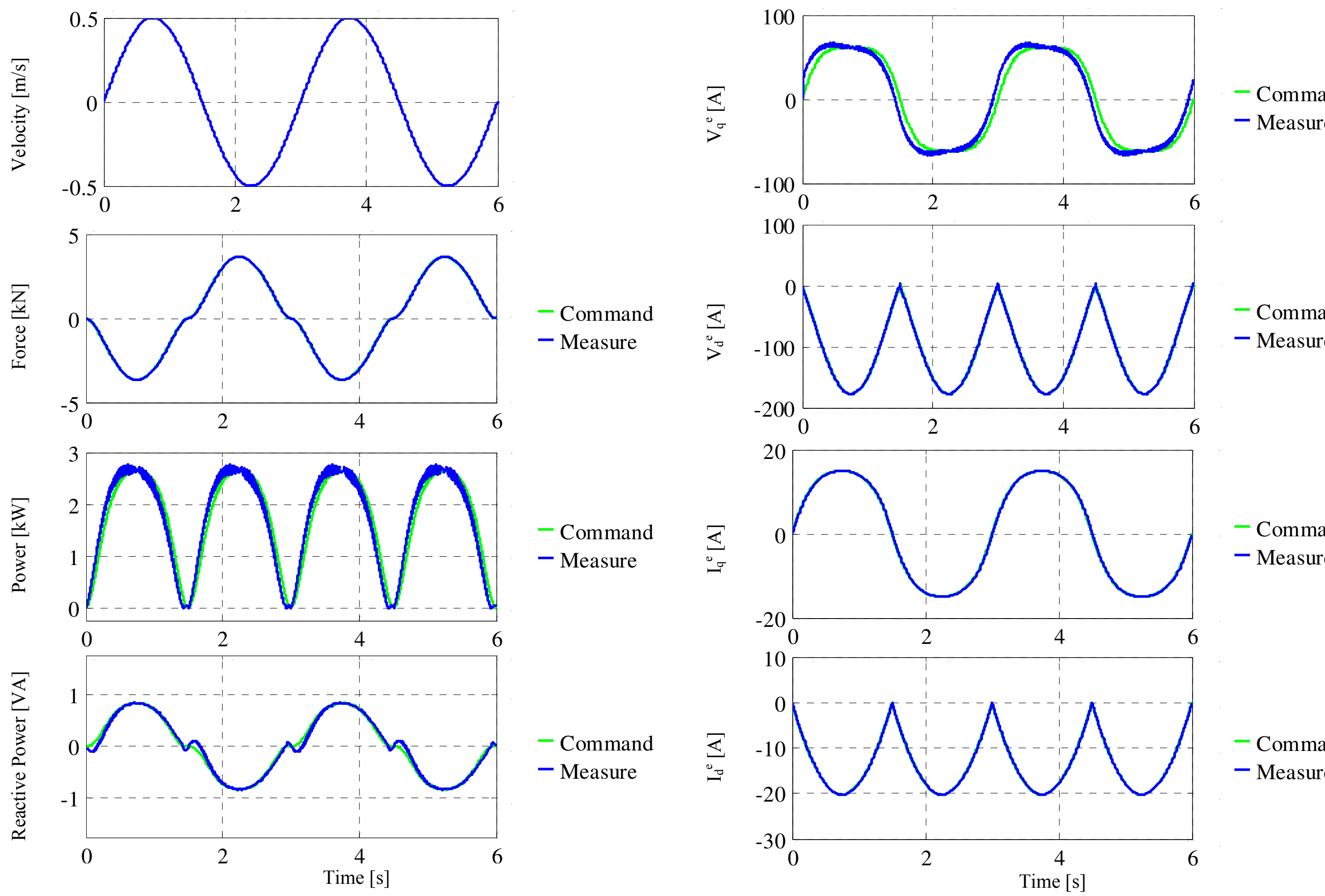

Figure 8. Waveforms obtained from computer simulation of the proposed system during a sinosoidal variation in the translator velocity

V. CONCLUSIONS

This paper has introduced a self-synchronous maximum power controller for the doubly-fed linear machine introduced in [1]. This controller aims to maximize power output by tracking velocity and maintaining orthogonality between the stator and translator flux.

While a traditional field oriented controller for a doubly-fed induction machine requires two 3ϕ inverters, the self-synchronous controller requires only one 3ϕ inverter. Even though the material savings of the self-synchronous controller comes at the cost of reduced controllability, it is evident in the controller's performance that a maximum power trajectory can be achieved with good power factor.

In addition to the self-synchronous controller's material savings, another benefit is its ability to produce large forces at low speeds much like a series DC machine. Since direct drive WEC operating speeds are low and require large reaction forces, this controller is well-suited for ocean wave energy applications.

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