Transient Stability Analysis of Battery with Fuel Cell Driven to Electric Powertrain

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***Abstract*—In the marine industry, fuel cell (FC) is being exploited as the primary power source with battery energy storage system (BESS) as complementary resource to be introduced for peak shaving and smoothing control in load fluctuation. As such, an integrated system of Proton Exchange Membrane Fuel Cells (PEMFC) with BESS is being developed to proposed to meet the dynamic three-phase load demand in a micro-grid configuration. In this paper, the transient stability verified by MATLAB/Simulink has shown that BESS is more adaptable than FC to meet constant and dynamic load demand. Moreover, there is an unstable power generation from PEMFC when a non-linear load is introduced. As such, in micro-grid's paradigm that consists of BESS that has the same energy capacity as FC, output power quality during transient period to electrified dynamic load is significantly enhanced. In addition, a proposed control algorithm is presented in this paper. Simulation studies have shown that the integration of PEMFC with BESS in micro-grid configuration offered better transient behaviour with lesser surge of 2%, as compared to BESS with transient surge of 225%.**

Keywords—Battery Energy Storage System, Fuel Cell, Micro-grid, Transient Stability, Renewable Energy Source

I. INTRODUCTION

Renewable energy sources (RES) installations have been increasing to meet the global power consumption demand inevitably due to its benefits in reducing carbon emission [1]. In today's world, RES including wind, solar, hydropower and biomass has been a promising technology to meet global energy demand [2]. There have been industrial projects in RES integrated with power grid to meet the energy need to reduce the carbon footprint [3]. In the marine industry, low carbon emission for fully electric ship vessels is a feasible solution for replacing conventional diesel or gas engine-powered energy systems [4 -6]. The fuel cell (FC) is a game changer now due to increasing interest for zero carbon emission in marine vessels [7]. In the latest development to achieve zero carbon emission for marine sector, FC is integrated with battery energy storage system (BESS) to enhance power quality to propulsion system on board.

In micro-grid configuration, traditional power generation (TPG) such as fossil fuel power generation integrated with battery energy storage system (BESS) can meet the power quality to load demand. Micro-grid which involves RES usually will incorporate BESS for peak shaving, load levelling and ensure reliability with power generation to load [8-10]. BESS is designed to provide quality power in energy generation to supply power to load in hybrid configuration [11]. BESS has been used in smoothing control of RES due to its fast response for state of charge (SOC) and discharge to power fluctuation from RES to react to load demand [12]. As such, RES by nature is of intermittency, will have to integrate with BESS to generate constant power supply for load demand at all time in off-grid configuration. However, the BESS integrated with Proton Exchange Membrane Fuel Cells (PEMFC), as compared with RES and TPG, has shown limitation by power and energy density constraints in the current research. To the best of our understanding, the transient stability of PEMFC with BESS configuration in micro-grid for uneven load is yet to be investigated and presented.

The Fuel cell system is considered of higher cost and the lifetime of fuel cell is shorter as compared with TPG and RES [13], [14]. However, PEMFC is achievable in zero carbon emission, offer quiet environment during power generation and its modular design enable easy for installation [15]. Thus, these tangible benefits have attracted attention of researchers in micro-grid with PEMFC to meet load demand. Even though the development and demonstration of PEMFC with BESS integration have been presented in the open literature, the transient period on PEMFC with BESS during test operation is yet to presented for proper sizing to meet the power quality to load.

The phenomenon of transient stability analysis in power system is viable where there are multiple power generation profiles on the micro-grid [16]. In early days, the analysis of transient stability in power system is of concern as computational tools are not too advanced at that time. In addition, it is very challenging to build a prototype to observe and study the transient period of the system. However, in the 20^{th} century of today, simulation has been the rule of thumb for verifying the transient stability in the design of power system [17]. A proposed transient behaviour mitigation of stand-alone fuel cell integrated with battery for power generation is presented in [18] but has yet to carry out feasibility study on large power generation in three-phase alternating current (AC) micro-grid.

This paper is organised as follows. Section II presents the overview of system architecture. Section III describes 10 scenarios for simulation and 8 case studies are discussed in Section IV. Section V presents proposed control algorithms.

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Lastly, conclusion and future work will be described in Section VI.

II. SYSTEM OVERVIEW

In this section, the system architecture is presented as follows. The detailed system describing the integration between PEMFC and BESS configuration is modelled in MATLAB/Simulink, as shown in Figure 1.

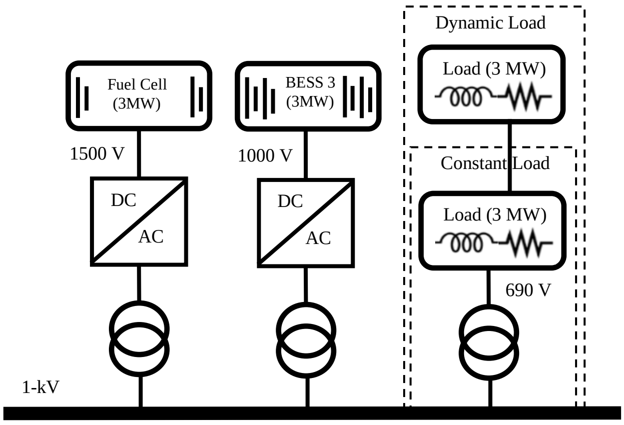

Fig. 1. Dynamic model of PEMFC with BESS configuration developed in MATLAB/Simulink

The system architecture which is of micro-grid configuration has constant load of 3 MW with fluctuating of load demand between 3 MW and 6 MW. The total energy generation to supply power in this system quantities the load demand of 6 MW. The micro-grid system used in the simulated model comprise of PEMFC and BESS, each with a rating of 3 MW in power generation applications. The load profile consists of constant rating of 3 MW and dynamic rating between 3 MW to 6 MW. The model is developed based on the PEMFC stack in MATLAB/Simulink. This validated model will generate direct current (DC) intially to be inverted into three-phase AC in 1-kV and followed by converting into 690V to load. The lithium–ion BESS in the simulation has been modelled with 3000-kWh lithium (ironFePO4) lithium-ion. It is a passive model operating under load demand. The BESS provides the energy capacity that is inverted from DC supply to AC in 11kV and then converted to 690 V to load.

A. *PEMFC Characteristics*

The temperature of PEMFC in operation is in the range of 70–100°*C* and the electrical efficiency is about 55%. The PEMFC model in simulation is assumed as follows:

1) Stack is fed with hydrogen and air and each cell has the same temperature and current density.

2) Maximum power generation is rated at 4000 kW with 4000V and 1000A.

3) Optimal power generation rated 3000 kW with 2000V and 1500A.

Figure 2 shows the output voltage and the load current (I-V) characteristic curve of PEMFC model with 3 MW and 4 MW power rating. The output voltage at the end of the curve drops as the load current increases. This characteristic curve is divided into 2 regions. The voltage drops across the fuel cell after it has reached its optimal power rating of 3 MW and low currents in 4 MW power rating is due to the activation loss inside the fuel cell. Thus, the voltage drops after it reaches its maximum voltage of 1800V due to the ohmic loss in the fuel cell stack.

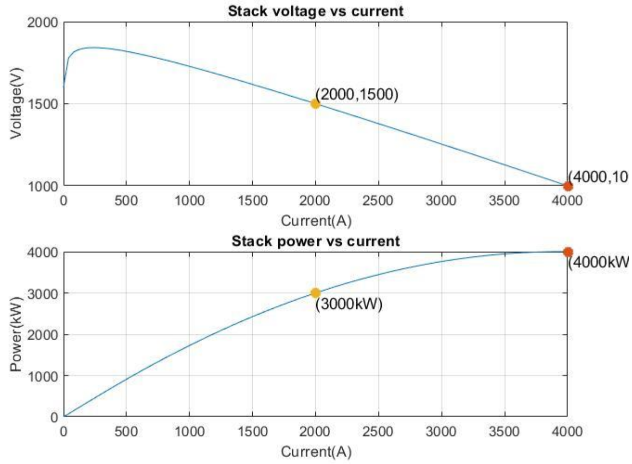

Fig. 2. Optimal and maximum power generation of PEMFC model developed in MATLAB/Simulink

B. *BESS Characteristics*

BESS react in passive mode of operation with a power rating of 3 MW, The BESS model in simulation is assumed as follows:

1) Nominal discharge output voltage rated 1050V for 1.5 hours.

2) Range of discharge current between 1818A and 36360A. Nominal discharge current of 1818A can be electrified to load for 1.5 hours.

Figure 3 shows the output voltage and the load current (I-V) characteristic curve of BESS model.

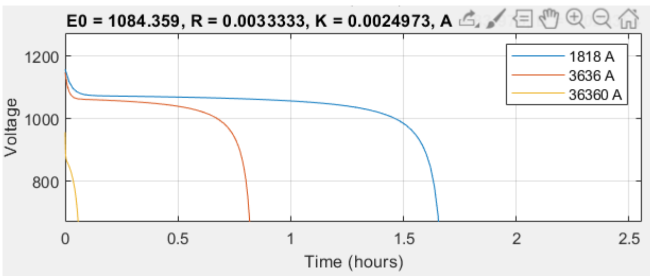

Fig. 3. Optimal and maximum power generation of BESS model developed in MATLAB/Simulink

III. TESTING SCENARIOS

In this section, ten test scenarios are described, as shown in Table I.

TABLE I. TEN SCENARIOS FOR SIMULATION

Scenario	Event
1	PEMFC is in starting phase to supply power to load.
2	BESS is in starting phase to supply power to load.
3	Continuous supply of power from PEMFC at 3 MW.
4	PEMFC is tripped and BESS is turned on at 3 MW.
5	Continuous supply of power from BESS at 3 MW.
6	BESS is tripped and PEMFC is turned on at 3 MW.
7	Continuous supply of power from BESS at 3 MW.
8	PEMFC is turned on at 3 MW.
9	Continuous supply of power from PEMFC at 3 MW.
10	BESS is turned on at 3 MW.

These ten scenarios are simulated in the MATLAB/Simulink in Section IV. The simulation study is based on the ability of the power system, to maintain electrical power to load when subjected to transient fault of individual power generation profile. The trip event which causes instability in the duration of transient power flow, will be investigated in the simulation. The simulation results are compared against individual power generation for maximum continuous deviation and maximum transient with recovery time. For a fair comparison, the system is assumed to have 1 PEMFC at 3 MW and 1 BESS at 3 MW running onboard. BESS with discharge and charge of power is not discussed in this paper as the primary focus will be on transient stability in power rating to load.

IV. SYSTEM SIMULATION RESULTS

A. Case 1

In this case, the system is started in Scenario 1 where there is PEMFC is in starting phase to supply power to load in Figure 4. The PEMFC is turned on for 10s at 3 MW in operation mode. In this case study, it can be seen from Figure 5 that there is a significant surge in output power to the load of 1.02 and the recovery time takes up to about 3s. In this case, it is shown that the output load power profile has a maximum transient deviation of 2% from its initial load of 1 p.u..

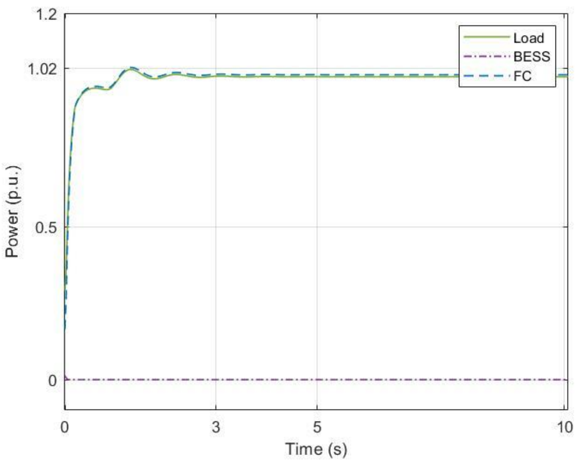

Fig. 4. PEMFC power generation in p.u. when power flow in p.u. to load is turned on (Pbase = 3 MW).

B. Case 2

Similarly, for load flow analysis in case 2, the system is started in Scenario 2 where there is BESS is in starting phase to supply power to load in Figure 5. The BESS is turned on for 10s at 3 MW in operation mode. In this case study, it can be seen from Figure 5 that there is a significant surge in output power to the load of 3.25 and the recovery time takes up to about 4.5s. In this case, it is shown that the output load power profile has a maximum transient deviation of 225 % from its initial load of 1 p.u.. The transient period in BESS is higher in transient deviation as compared to PEMFC when supplying power to load.

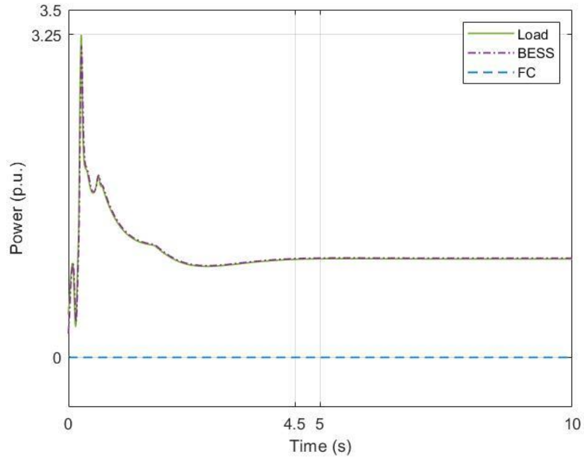

Fig. 5. BESS power generation in p.u. when power flow in p.u. to load is turned on (Pbase = 3 MW).

C. Case 3

In this section, the system is started in Scenario 3, and switched to Scenario 4. In Scenario 3 where there is continuous supply of power from PEMFC at 3 MW, BESS is turned on when the PEMFC is tripped and BESS is running in operation mode. It can be seen from Figure 6 that there is a significant surge in output power to the load of 3.9 and the recovery time takes up to about 5.7s. In this case, it is shown that the output load power profile has a maximum transient deviation of 290% from its initial load of 1 p.u.

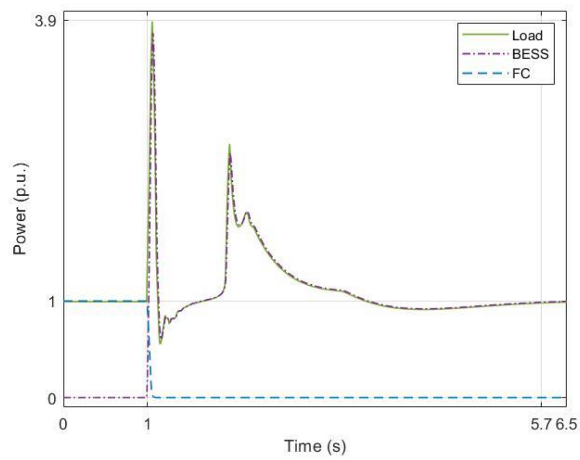

Fig. 6. PEMFC and BESS power generation in p.u. when power flow in p.u. to load is turned on (Pbase = 3 MW). BESS is turned on when the PEMFC is tripped.

D. Case 4

In this Case, the system is started in Scenario 5 and switched to Scenario 6. In Scenario 5 where there is continuous supply of power from BESS at 3 MW, PEMFC is turned on when the BESS is tripped and PEMFC is running in operation mode. It can be seen from Figure 7 that there is a significant dip to 0.1 p.u followed by surge in output power to the load of 2.2 p.u. and the recovery time takes up to about 3.5s. In this case, it is shown that the output load power profile has a maximum transient deviation of -90/120% from its initial load of 1 p.u..

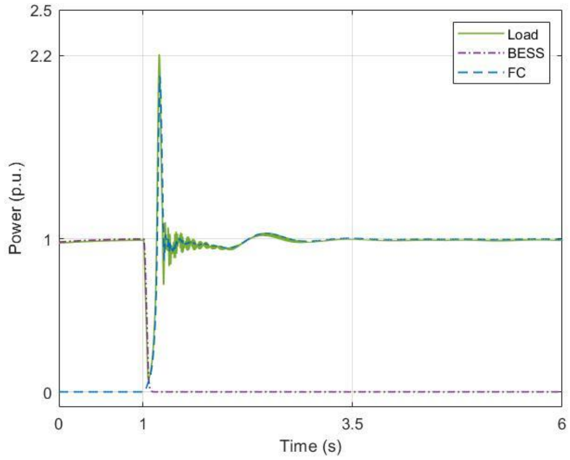

Fig. 7. PEMFC and BESS power generation in p.u. when power flow in p.u. to load is turned on (Pbase = 3 MW). PEMFC is turned on when the BESS is tripped.

E. Case 5

In this Case, the system is started in Scenario 7 and switched to Scenario 8. In Scenario 7 where there is continuous supply of power from BESS at 3 MW, PEMFC is turned on and PEMFC with BESS are running in operation mode. It can be seen from Figure 8 that there is a significant surge in output power to the load of 2.38p.u. and the recovery time for transient period takes up to about 4s. In this case, it is shown that the output load power profile has a maximum transient deviation of 38% from its initial load of 1 p.u..

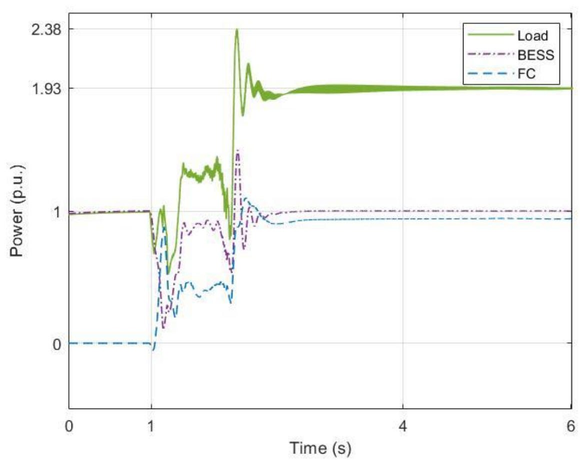

Fig. 8. PEMFC and BESS power generation in p.u. when power flow in p.u. to load is turned on (Pbase = 3 MW). BESS is in operation mode when the PEMFC is turned on.

F. Case 6

In this section, the system is started in Scenario 9 and switched to Scenario 10. In Scenario 9 where there is continuous supply of power from PEMFC at 3 MW, BESS is turned on and PEMFC with BESS are running in operation mode. It can be seen from Figure 9 that there is a significant surge in output power to the load of 2.29 and the recovery time for transient period takes up to about 4s. In this case, it is shown that the output load power profile has a maximum transient deviation of 29% from its initial load of 1 p.u..

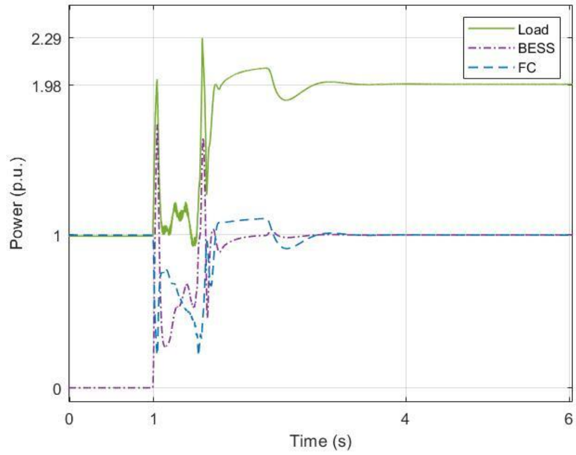

Fig. 9. PEMFC and BESS power generation in p.u. when power flow in p.u. to load is turned on (Pbase = 3 MW). PEMFC is in operation mode when the BESS is turned on.

V. Conclusion and Future Work

In this paper, the simulation study on the transient stability of the integration of PEMFC with BESS in micro-grid configuration is presented. The simulated model has shown PEMFC delivers start up to load offered better transient behaviour with lesser surge of 2% as compared to BESS with transient surge of 225%. In addition, the simulation has shown that PEMFC with BESS in transient stability for power generation can be designed to enhance power quality to three-phase AC load transient in the micro-grid configuration. The proposed control algorithm has demonstrated feasibility in transient stability for power flow to load performance in a micro-grid. This model was validated by the simulation results show that BESS has great promise in power generation applications with dynamic load at peak rating and minimum rating. In future work, different types of energy storage for simulation to study transient stability effects will be studied.

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