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Modeling, Simulation, and Comparison of Wind Energy Voltage Fluctuation Mitigation Methods

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Highlights

- A Power System Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) model for the Wind Energy Conversion System (WECS) connected to a "weak" grid with a load to illustrate voltage fluctuation is presented. Simulation results show voltage fluctuations as a power quality (PQ) issue has been reduced when mitigating systems such as a Battery and a STATCOM were introduced.
- Results suggest that both real and reactive power support are essential for addressing voltage fluctuation issues at the Point of Common Coupling (PCC)
- This study is proposed as a suitable tool to achieve the outcomes-based education prescribed by the Commission on Higher Education (CHED) Memorandum Order No. 88. Under Article IV Section 6 (CHED, 2017). The following expected outcomes for the Bachelor of Science in Electrical Engineering (BS EE) are specifically identified with this study: *a*. Apply knowledge of mathematics and sciences to solve complex engineering problems; *b*. Develop and conduct appropriate experimentation, analyze and interpret data; *c*. Design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability, in accordance with standards; *h*. Understand the impact of engineering solutions in a global, economic, environmental, and social contex; *j*. Articulate and discuss the latest developments in the field of electrical engineering; and *k*. Apply techniques, skills, and modern engineering tools necessary for electrical engineering practice.
- This study may be considered as components to the courses listed in the minimum curriculum for the BS EE program as stated by Article V Section 11 of the same memorandum. These subjects are: *a*. Electrical Apparatus and Devices; *b*. Electrical Machines; *c*. Power System Analysis; *d*. Fundamentals of Power Plant Engineering Design; and *e*. Feedback and Control Systems.

Abstract

The increasing integration of wind energy power plants into the electric power system introduces undesirable effects in terms of Power Quality (PQ). Likewise, it introduces a growing demand for a more competent workforce. A base system composed of the Wind Energy Conversion System (WECS), "weak" grid, and load was modeled with the use of the PSCAD/EMTDC to demonstrate the primary PQ concern of this study - Voltage Fluctuation. A Battery System, a STATCOM, and the combination of these two are the mitigation methods that were compared. The Battery System's phase angle was controlled to compensate for the WECS or load real power while the STATCOM's voltage magnitude was managed to govern the reactive power flow in the system by monitoring the RMS voltage at the PCC. The combined method illustrated significant Point of Common Coupling (PCC) voltage improvements suggesting that both real and reactive power support are necessary to mitigate voltage fluctuation.

This research of utilizing a modern power system simulation platform for observing WECS operation, voltage fluctuation, and mitigation methods can be incorporated into a number of required courses prescribed by CHED such as Electrical Apparatus and Devices, Electrical Machines, Power System Analysis, Fundamentals of Power Plant Engineering Design, and Feedback and Control Systems to address the expected outcomes *a, b, c, h, j, k* for the BS Electrical Engineering program.

Key Words: Power Quality; Voltage Fluctuation; WECS; Battery System; STATCOM

1. Introduction

Wind Energy is becoming more popular as the world is shifting to the use of renewable energy sources. Wind Energy plants operate by using wind to provide kinetic energy for the rotation of the blades, transferred to the mechanical shaft then to the electrical generator where electromechanical conversion occurs. The electrical power is then fed to the electrical grid, either directly or via a power electronic converter. However, due to its intermittency, it presents negative effects on power system Power Quality (PQ). PQ issue is defined as any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of custormer equipment (Dugan et al., 2012)

Static VAR Compensators can be used as a substitute for the capacitor banks that can prevent over and undervoltages (Taherzadeh et al., 2013); energy storage device installation using batteries, supercapacitors, and superconducting magnetic energy storage can mitigate voltage fluctuations (Diaz-Gonzalez et al., 2012); passive and active harmonic filters are often used to remove unwanted harmonics as well as to prevent the formation of harmonic resonances (Kumar and Zare, 2014; Grady, 1990). Furthermore, corresponding control systems must be developed to allow those general solutions to work in sync with the grid.

These developments in the electric power system requires new competencies from our modern electrical engineers. CHED's Memorandum Order No. 88 (CHED, 2017) prescribes an outcome-based education leading to competency-based standards expected of BS Electrical Engineering graduates regardless of the institution they graduated from. The Outcomes-Based Teaching and Learning (OBTL) is a student-centered approach where the courses contained in the program are designed to achieve intended student outcomes. Its focus are statements of what students should be able to do with what they know after completing a course. A curriculum for the required core courses were included to ensure that students can understand and articulate the nature of their special role and their work's impact in society. Expected program outcomes were also included as listed from *a* to *l* of the memorandum's Article IV Section 6.

This paper is arranged as follows: Sections 2 and 3 presents the development of a test system suitable for time-domain simulation that illustrates voltage fluctuations introduced by a Wind Energy Converter System (WECS) connected to a weak grid. Mitigation techniques such as a STATCOM and battery systems were introduced to minimize voltage fluctuations at the point of common coupling (PCC). Section 4 on the other hand describes the educational value of conducting system studies such as this.

2. Simulation Setup

This section presents the developed simulation setup for a power system that consists of a WECS connected to a weak grid which causes voltage fluctuations at the point of common coupling. Mitigation methods such as a battery storage system and a STATCOM where introduced to reduce voltage fluctuations.

2.1 Building the "Weak" Grid, Load, and Wind Energy Conversion System (WECS) Models

2.1.1 Base System

The base system shown in Figure 1 aims to demonstrate the occurrence of voltage fluctuations when the WECS is operating at variable wind speed. It is important to characterize the rest of the grid as "weak" by adding a series R-L-C and increasing the transformer's positive series leakage reactance in order to emphasize the fluctuations. The R-L load was computed by setting the PCC at 13.8 kV and allowing it to absorb 4 MVA with an assumed 0.9 lagging power factor.

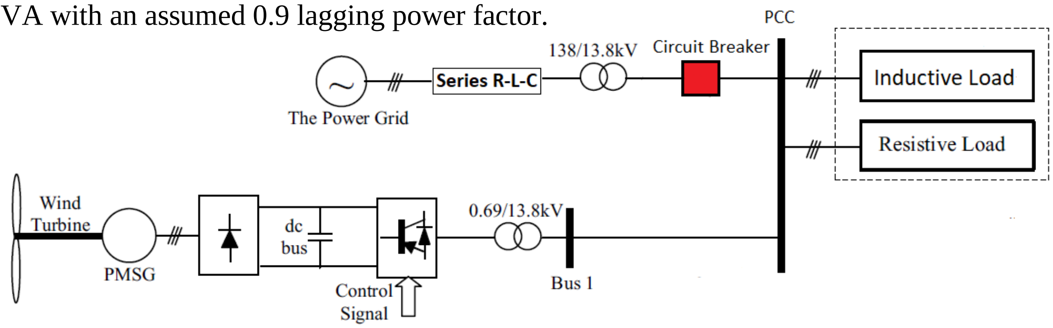


Figure 1. Base System Schematic.

2.1.2 Wind Source, Wind Turbine, Governor, and Permanent Magnet Synchronous Generator (PMSG)

The mechanical torque output of the turbine was processed to obtain the speed input needed by the PMSG to produce a three-phase sinusoidal voltage. Constant wind speed was set at 13 m/s and variable wind speed operation can be obtained by simply enabling the "ES" parameter of the wind source block.

2.1.3 Power Electronics Converter

The three-phase voltage produced by the PMSG will then go through a series of Power Electronic Converters starting with a rectifier which will then be smoothened by a capacitor with a value that can handle the required energy.

The inverter is made up of six IGBT-diode combinations. The controller was designed such that the WECS will deliver power in an uncontrollable manner to properly observe the effects of wind speed variation to both power and voltage. The controller utilized the SPWM technique with an arbitrary 3-phase sinusoid being compared to a triangular wave to obtain the IGBT's firing pulses. Some pulses were then delayed to avoid overlapping of IGBT operation. To get the desired sinusoidal voltage and magnitude, a low pass-filter was connected to the output attenuating higher levels of frequencies above 60 Hz. The L and C values were adjusted accordingly.

2.2 Building the Battery System Controller Simulation Model

The controller manages the battery's inverter firing pulses and solely focuses on adjusting the phase difference between the battery and the test system. For a given phase difference, the battery can either absorb or deliver real power in an attempt to smoothen the real power at the load resulting into less voltage fluctuation. The battery controller was designed by first establishing the real power absorption and generation versus phase difference characteristics. This was done by allowing the test system to operate at a constant wind speed with the connected battery system and manually adjusting the phase angle of the battery's inverter such that after a small simulation duration, it pauses, adjusts to increase the battery's voltage lag by 5 degrees, then resumes again. The angle spans from zero to 360 degrees to also observe the real power when it is already leading. This was done in Power System Computer Aided

Design (PSCAD) by manually pausing the simulation and adjusting the phase angle through the use of a slider. This characteristic plot then allows the formulation of the ideal equation shown in Eq. 1 whose form gets followed by the controller.

$$P\_battery\ (\mathrm{MW}) = -1.1525 \sin(PS-7) - 0.2831 \qquad (1)$$

Where $P\_battery$ is the amount of real power to be absorbed or generated and PS is the battery's phase shift with respect to the base system in degrees. The adjusted R-squared value is 0.9953 signifying that Equation 1 is a good fit to relate the load or WECS real power to the Battery's phase angle.

2.3 Building the Static Compensator (STATCOM) Controller Simulation Model

On the other hand, the STATCOM's controller was designed such that the difference in voltage magnitude between the base system and the STATCOM determines the reactive power flow. The amount of needed reactive power is determined from the difference of the actual Point of Common Coupling (PCC) RMS voltage and a set reference value which is 0.9375 p.u. for this study. The same method of pausing, manual value change, and resuming was done but instead of changing the phase angle, the voltage magnitude became the dependent variable for the characteristic of the reactive power exchange. The change was done from zero to one with an increase of 0.05 for each test duration. From the set of actual values obtained from the test, an ideal equation was again computed for the relationship between PCC RMS voltage difference, reactive power flow, and controller sinusoid magnitude. The Microsoft Excel's regression analysis was utilized to obtain Equations 2 and 3.

$$Q\_STATCOM\ (\mathrm{MVar}) = 28.29V_{pcc,change} + 0.093 \qquad (2)$$

$$Q\_STATCOM\ (\mathrm{MVar}) = -2.533Mag + 1.0915 \qquad (3)$$

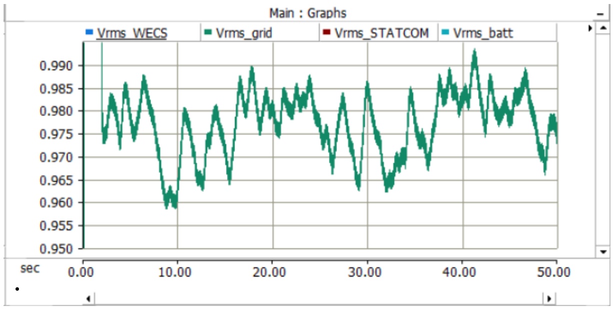
Where $Q\_STATCOM$ is the amount of reactive power to be absorbed or generated, $V_{pcc,change}$ is the change in PCC voltage with 0.9375 as the base value, and Mag is the STATCOM's inverter Sinusoidal Pulse Width Modulation (SPWM) Controller magnitude value. Equations (2) and (3) relate the variables of interest significantly with adjusted R-squared values of 0.9995 and 0.9982 respectively

Lastly, both mitigation methods were combined with the test system with the battery compensating for the WECS real power while the STATCOM's operation was based on the PCC RMS Voltage. The simulation was done without further changes in the discussed controllers above.

3. Results and discussion

3.1 Variable Wind Speed

By enabling the noise component of the wind source block, a variable wind speed input can be directed to the turbine. This section shows the steady-state response of the system to this varying input. Figures 2 and 3 for the PCC voltage and the histogram plot.



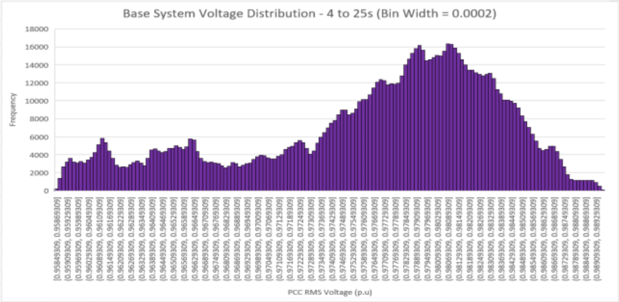


Figure 2. Voltage Fluctuation at the PCC.

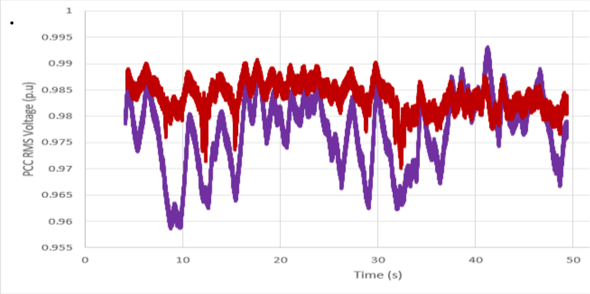
Figure 3. Histogram for PCC Voltage values.

From these results, the PSCAD model for the WECS-weak grid-load shows the expected voltage fluctuation during variable wind speed operation. The Histogram also shows the scattered PCC voltage values.

3.2 Battery System Mitigation

3.2.1 Load Real Power Compensation

This section describes the results by having the battery compensate for the load's absorbed real power. Figure 4 shows the overlapped PCC voltages of the base system and when the battery was applied. The histogram in Figure 5 reveals an improvement as voltage values at the outlying ranges were reduced.



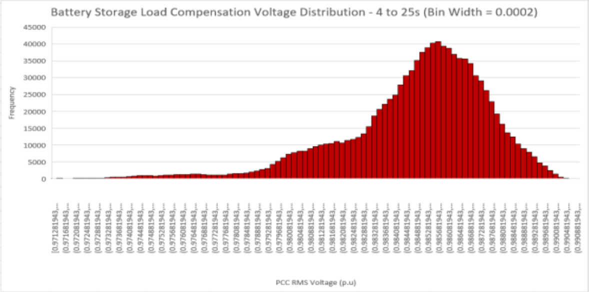
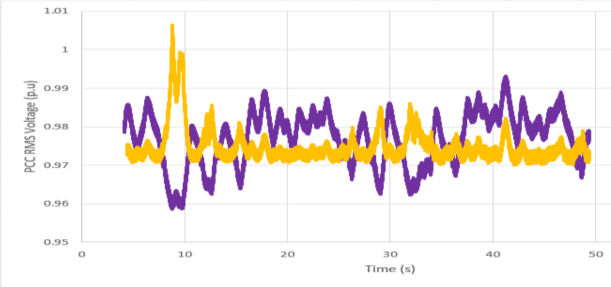


Figure 4. PCC voltages:
Purple for base system, red for with battery.

Figure 5. Histogram with battery – load compensation.

3.2.2 WECS Real Power Compensation

With the same battery, the compensation target changes to WECS. Figure 6 for the overlapped PCC voltages of the base system and when the battery was applied and the histogram in Figure 7.



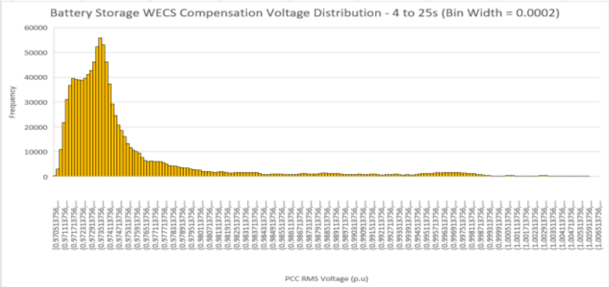
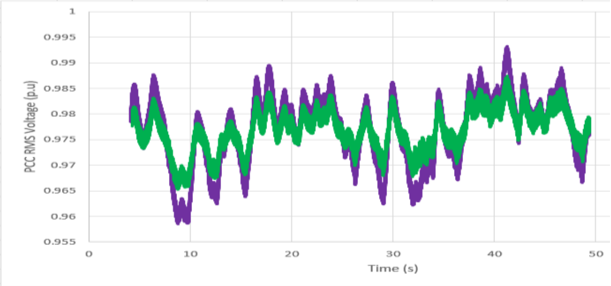


Figure 6. PCC voltages:
Purple for base system, yellow for with battery.

Figure 7. Histogram with battery – WECS compensation.

3.3 STATCOM Mitigation

This section presents the results for having the STATCOM compensate for the system's reactive power by measuring the corresponding changes in the PCC voltage. Figure 8 compares the voltage form the base system revealing that the range of fluctuation was decreased followed by the histogram in Figure 9.



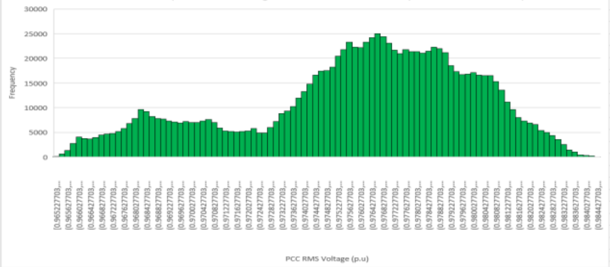


Figure 8. PCC voltages:
Purple for base system, green for with STATCOM.

Figure 9. Histogram with STATCOM Q compensation.

3.4 Combined Battery System and STATCOM

This system was simply modeled by connecting the two mitigation methods, along with their controls, at the PCC of the test system. Figures 10 and 11 for the PCC RMS voltage comparison and histogram. Looking at the RMS voltage, the shape is the same as the Battery Storage WECS compensation configuration but with less values of voltage spikes. This result shows that the battery storage does a good job in compensating the needed real power and the STATCOM helped in compensating the undesired reactive power from the battery. Also the histogram reveals that outlying voltage ranges were further reduced and became more compressed at certain voltage values.

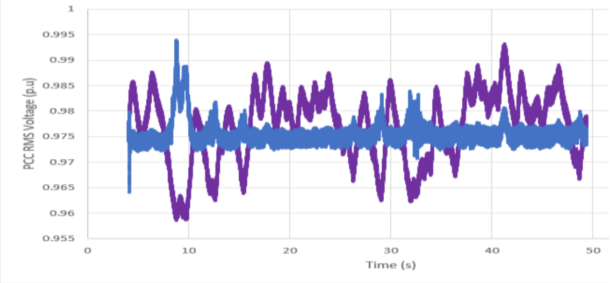


Figure 10. PCC voltages:
Purple for base system, blue for combined method.

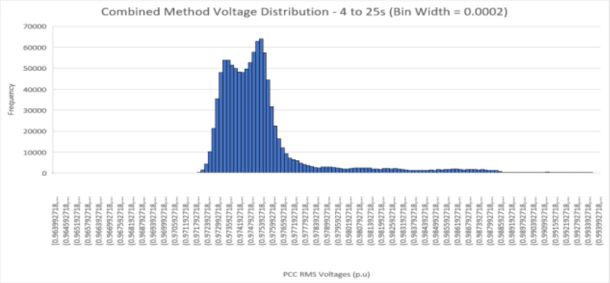


Figure 11. Histogram for combined method.

3.5 Summary and plot comparison of the different mitigation methods

Figure 12 compares all of the PCC voltages under varying wind speed condition.

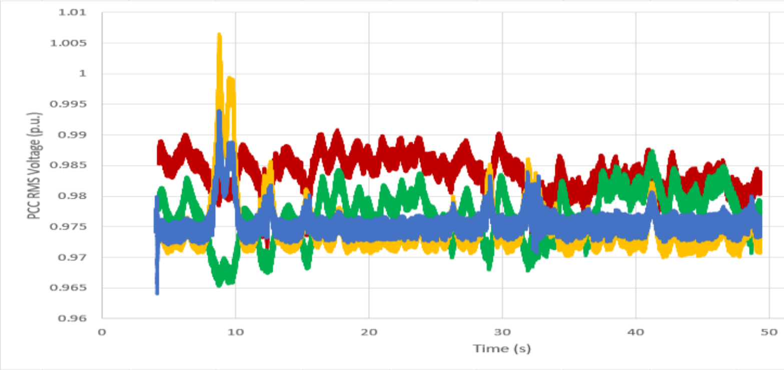


Figure 12. Summary of all PCC voltages from the different methods: Blue for combined method, Yellow for Battery at WECS, Red for Battery at load, and Green for STATCOM.

Red for the battery at load real power compensation, Yellow for the battery at WECS real power compensation, Green for the STATCOM, and Blue for the combined method. It can be seen that the combined method provided the best mitigation result with spike values lower than the Battery-WECS.

4. Educational Value of this System Study

Although this work is primarily a research activity, the authors offer here its utility for instruction. The parts of this project, listed one to six below, are capable to support CHED's memorandum expected outcomes *h, j, c, a, b,* and, *k* correspondingly.

1. Tackling the PQ issue of Voltage Fluctuation by realizing its importance for the industrial, commercial, and residential sectors: Objective *h. Understand the impact of engineering solutions in a global, economic, environmental, and social context*;

2. Exploring proposed solutions from recent published researches and comparing through modeling based on the researcher's interpretations and methods: Objective *j. Articulate and discuss the latest developments in the field of electrical engineering*;
3. Building and setting the parameters of the WECS, load, and control systems according to the desired system characteristics: Objective *c. Design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability, in accordance with standards*;
4. Illustration and appreciation of the theory of how phase angles and voltage magnitude difference can affect the real and reactive power flow in the system: Objective *a. Apply knowledge of mathematics and sciences to solve complex engineering problems*;
5. Histograms and plot comparison to gather reasonable interpretations from the simulation results of the different mitigation systems: Objective *b. Develop and conduct appropriate experimentation, analyze and interpret data*; and
6. Utilize PSCAD/EMTDC software to build the WECS and mitigation models. The electrical engineering concept of "Power Flow" served as the foundation of building both Battery and STATCOM controllers: Objective *k. Apply techniques, skills, and modern engineering tools necessary for electrical engineering practice*.

Moreover, this study may also be included to the following required courses to achieve such outcomes.

a. Electrical Apparatus and Devices – software allows the use of transformers, circuit breakers, diodes, thyristors, buses, line models, and many more. Along with a generation model, such components can build a simple system whose operation of each component can be observed.
b. Electrical Machines – the Permanent Magnet Synchronous Generator (PMSG) used in this study illustrated its operation that was dependent on the output torque of the turbine which is close to the actual wind conversion systems.
c. Power System Analysis – the theory "Phase Angle controls Real Power while Voltage Magnitude difference for Reactive Power" was clearly demonstrated by the mitigation method's controllers. Such important concepts behind Power Systems can be appreciated through these simulations along with other possibilities like Short Circuit analysis and Load Flows.
d. Fundamentals of Power Plant Engineering Design – the platform offers the basic components of a wind, solar, and hydroelectric plants. A wind source, turbine, and governor are already modelled into blocks whose code satisfy their actual governing equations of operation. Users have the freedom to enter their desired parameter values.
e. Feedback and Control Systems – although the controllers were only built with simple mathematical equations, this study presented the method of measuring certain system parameters, apply necessary processing, then return the final value to the system to obtain the desired operation.

5. Summary and Recommendations

A Wind Energy Conversion System (WECS) connected to a "weak" grid and load was modeled in PSCAD/EMTDC to illustrate the Power Quality issue of voltage fluctuation during variable wind speed operation. The Battery System and STATCOM were compared and best mitigation results were observed with the combined method suggesting that both real and reactive power support are needed for fluctuation mitigation purposes. The models, simulation results, and simulation software are capable of being added as instructional materials to a number of prescribed core courses by CHED namely: Electrical Apparatus and Devices, Electrical Machines, Power System Analysis, Fundamentals of Power Plant Engineering Design, and Feedback and Control Systems. Such materials can guide the students towards the expected outcomes *a, b, c, h, j, k,* under the memorandum's Article IV Section 6, for the BS Electrical Engineering program.

Due to the limited capabilities on the free version of the PSCAD/EMTDC, a licensed version is required. An open-source program can be explored like the Electromagnetic Transient Program – Alternative Transient Program (EMTP-ATP) except that it requires a licensed faculty to allow students to apply for a software license. Lastly, moving forward with this research can be done by developing a set of assessment tools that can evaluate the achievement of the learning outcomes.

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