Multi-Machine Stability of a Wind Farm Embedded Power System using FACTS Controllers

S.N. Deepa[1], J. Rizwana[2]
[1]Associate Professor, [2]Research Scholar
Anna University Regional Centre, Coimbatore, Tamilnadu, India
[1]deepapsg@gmail.com,
[2]rizwana.scholar@outlook.com

***Abstract*--Wind Energy is one of the cheapest available renewable sources of energy. Now-a-days the demand for electricity increases drastically. A number of wind farms are already in operation and more are planned or under construction due to the increasing demand of the bulk amount of the electricity. It is must to identify the interactions between the Wind Turbines and the Power System. Here the Power System consists of many generating stations which forms the Multi-Machine System. The objective of this paper is to improve the Power Quality in a Wind Farm embedded Multi-Machine Power System and to maintain stability in the system by using FACTS controllers. Generally when a fault occurs in Wind Farm embedded Multi-Machine Power System the wind farm induction generator is isolated from the power system. After removal of the fault from the power system the wind farm induction generator is connected back to the power system. The wind farm induction generator absorbs more reactive power from the grid while re-connecting back to the power system. As a result, there will be more demand for reactive power in the system. This in turn will lead to voltage dip and other undesirable effects. In this paper FACTS controllers are used to supply reactive power to the wind farm embedded power system during fault and while re-connecting the wind farm induction generator back to the power system. These FACTS controllers supply reactive power during the re-connection of the wind farm induction generator to the power system, thereby improving the voltage profile which in turn leads to the power system stability.**

Index Terms-Multi-Machine Stability, Induction Generator (IG), Active Power (P), Reactive Power (Q), Flexible AC Transmission Systems (FACTS), Static VAR Compensator (SVC), Static Compensator (STATCOM), Unified Power Flow Control (UPFC)

I. INTRODUCTION

The depletion of fossil fuels from the 21st century due to its rising concerns over energy security and global warming; it led to the expansion forms of interest in renewable energy. Even due to the sudden rise of oil prices from 2003, the industrial users utilising petroleum shifts their utility towards coal and natural gas. The natural gas had its own supply problems; hence wind power replaced the natural gas usages in production of electricity.

The Commercial Wind Power starts fledging at a robust growth rate of about 30% every year due to its large wind resources and improved wind farm management. Wind energy is considered to be clean, sustainable and affordable energy source to improve the electricity generation [1,2].

Hence by using the improving techniques and implementing innovative methods to reduce costs and low environmental impact, wind energy seems one of the better methods certain to play a major part in the future world's energy. While considering about the issues in the wind power, the focus on the power quality shifts to the stability problem recently, when the wind power penetration continually increases. Hence, the planning and operation of the plant becomes much important to consider the impact on the wind power when it is embedded with the power system [3]. The loss of synchronism of some generators violating the field current limits also leads to the instability problem [4].

In the past, the stability of the wind farm embedded in a power system was maintained using the proper selection of the proportional gain of the speed and power factor controller. The Crowbar circuit and the rotor side converters are used to improve the stability during fault conditions [5].

The frequency converters are used to control the torque and reactive power in the wind turbines which acts as a controlled voltage source converter [6]. The back-to-back PWM converters along with the MPPT techniques are used latter to improve the high efficiency in the wind turbine induction generator [7].

In this paper, the FACTS controllers are used, which minimizes the reactive power and other voltage drops to improve power quality of the power system; hence in order it maintains stability even during fault conditions.

II. WIND TURBINE MODEL

The Aerodynamics concept was first analyzed in Wind Turbine by Betz and Glauert in late 1920s and early 1930s. Wind Turbines are designed to capture the Kinetic Energy present in the wind and convert it into electrical energy. Wind Turbine power production depends on interaction between the wind turbine rotor and the wind. The mean power output is determined by the mean wind speed.

Power Output of the wind is given by;

$$P_m = \frac{1}{2}\rho A {V_w}^3 \quad (1)$$

In the above equation;

ρ is Air Density (1.225 kg/m^3);

A is Area of Swept circle by Blades (m^2);

V_w is Wind Speed.

In practice, wind turbines are limited to two or three blades due to the combination of structural and economic considerations. Hence the amount of power they can extract is closer to about 50% (0.5 times) of the available power. The ratio of the extractable power to the available power is expressed as the rotor Power Coefficient (C_p).

$$P_m = \frac{1}{2} C_p \rho A {V_w}^3 \quad (2)$$

The Power Coefficient (C_p) depends mainly on the Tip Speed Ratio (λ). The TSR is the ratio of the blade tip speed to the wind speed. Hence it is given by;

$$\lambda = \frac{\frac{N\pi D}{60}}{V_w} \quad (3)$$

where,

N is the Rotor Speed (rpm);

D is the Diameter of the Wind Turbine Blade.

While consulting with the manufacturer documentation, the power curves of the individual win turbine shows a high degree of similarity. Hence the usage of different approximations of C_p (λ) curve is not necessary for different constant speed wind turbine in power system dynamics. In this paper, the following general approximation is used:

$$C_p(\lambda,\Theta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\Theta - C_4\Theta C_5 -\right) e^{\frac{-C_7}{\lambda_i}} \quad (4)$$

where,

$$\lambda_i = \frac{1}{\frac{1}{\lambda + C_8\,\Theta} - \frac{C_9}{\Theta_3 + 1}} \quad (5)$$

Here C_1 to C_9 are constant values.

By using these mathematical equations, we can able to design the wind turbine model.

III. FACTS CONTROLLERS

The FACTS Controllers provides smoother operation by using mechanical switches over the other power electronic devices. It has a less maintenance and the system will have an increased lifespan. In order to improve the performance of the Wind Power Plant by absorbing or delivering the reactive power from the grid, the simplest way to use is FACTS devices.

A. Static Var Compensators (SVC)

The SVC is a device, which brings the system closer to UPF. If the power system's reactive load is capacitive (leading), the SVC will use reactors to consume VARs from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage. When system voltage is low, the SVC generates reactive power (SVC Capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of the coupling transformer.

B. STATCOM – Configuration

STATCOM is a new breed which compensates reactive power and it is based on VSC technique. This controller adjusts the output current to control the reactive power injected at the bus. It is connected in shunt with the AC power system. When system voltage is low, the STATCOM inject reactive power. When system voltage is high, it absorbs reactive power from the system.

C. Unified Power Flow Controller (UPFC)

It is the most versatile member of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow on power grids. The UPFC uses a combination of a shunt controller (STATCOM) and a series controller (SSSC) interconnected through a common DC bus. The assumptions made in this controller are series transformer inductance and resistance are negligible compared to transmission-line impedance.

To allow control of the active and reactive power line in addition, the UPFC provides an additional degree of freedom. The shunt connected converter operates as a STATCOM which controls voltage by absorbing or generating reactive power. Both the series and shunt converters use a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSCs use forced-commutated Power Electronic devices (GTOS, IGBTs or IGCTs) to synthesize a voltage from a DC voltage source.

TABLE I. Machine Parameters used in Simulation

Wind Turbine	
Diameter	28.5 m
Area of Swept Circle	638 m^2
Speed (High/Low)	39.8 rpm / 26.5 rpm
No. of Blades	3
Generator	
Type	Asynchronous
No. of Poles	4
Rated Output	250 KW
Main Voltage	400 V
Frequency	50
Performance Data	
Rated Wind Speed	14 m/s
Cut-in Wind Speed	3.5 m/s
Cut-out Wind Speed	25 m/s
Max Power Coefficient	0.45
Generating Station 1	1500 MVA, 11kV, 50Hz
Generating Station 2	2500 MVA, 11kV, 50Hz
Fault	3-Phase fault
Wind Turbine	3

IV. WIND FARM EMBEDDED MULTI-MACHINE POWER SYSTEM

The two generating stations (1500 MVA, 2500 MVA) each of which generates 11kV is transmitted to the load through transmission lines after it is stepped-up and stepped-down by a transformer which forms the primary distribution. The distribution to the load forms the secondary distribution. The wind turbine is modeled using the equations. Then this model is coupled with IG.

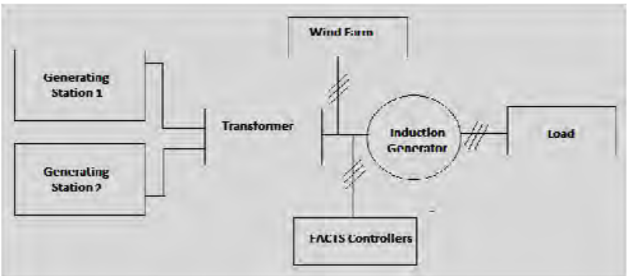

Fig 1: Multi-Machine embedded Wind Farm Induction Generator

The Wind Turbine Induction Generator is embedded with the Multi-Machine Power System. The fault is introduced in the power system and the response is observed using simulation results. During fault condition, the wind farm induction generator is isolated from the system and after the removal of the fault the active and reactive power is absorbed from the load which causes voltage drop leading to instability. Hence to reduce the voltage drop and to improve the power quality, the FACTS Controllers are introduced in the power system. The FACTS Controllers like SVC, STATCOM and UPFC Controllers are used and results are compared to determine which controller fits perfectly for the system to reduce voltage dips.

V. SIMULATION RESULTS AND DISCUSSIONS

Simulation results are determined by using MATLAB/SIMULINK toolbox. The Output of the Voltage, Current, Real and Reactive Power are determined for the Wind Farm embedded Multi-Machine Power System with and without FACTS Controllers before and after fault are shown in below figure 2-15. Here the wind farm embedded power system with 4 cases is considered:

Case 1: Wind farm embedded multi-machine power system with and without fault

Case 2: Wind farm embedded multi-machine power system with SVC with and without fault

Case 3: Wind farm embedded multi-machine power system with STATCOM with and without fault

Case 4: Wind farm embedded multi-machine power system with UPFC with and without fault

A. Wind Farm embedded Multi-Machine Power System without FACTS Controllers

The fault is introduced for t=0.02-0.08 sec. The original system is restored after 0.08 sec. Soon after the clearance of the fault, there is absorption of reactive power. Also the output voltage and current has been dropped much.

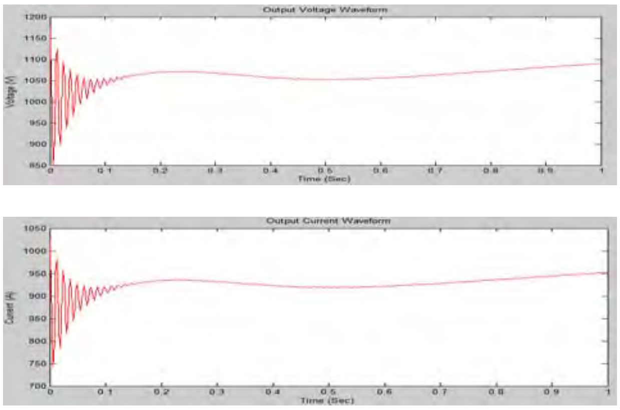

Fig 2: Output Waveform of the Wind Farm Embedded Multi-Machine Power System

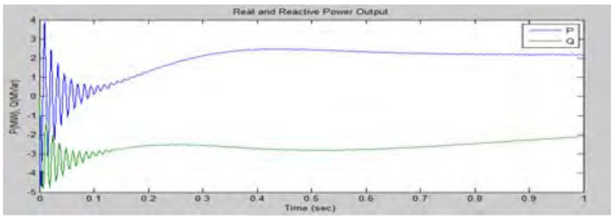

Fig 3: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System

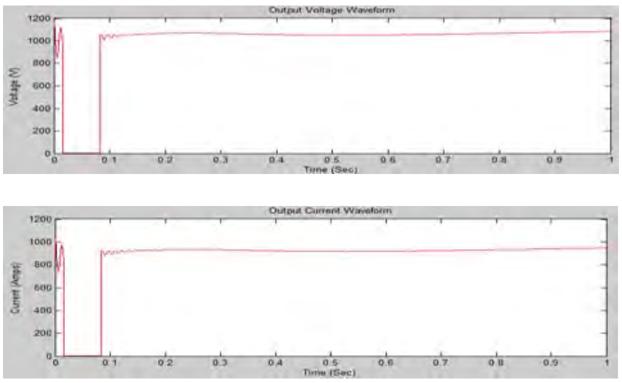

Fig 4: Output Waveform of the Wind Farm Embedded Multi-Machine Power System (with fault)

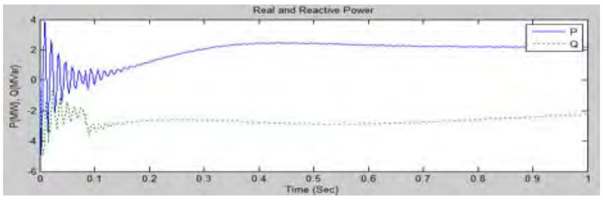

Fig 5: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System (with fault)

B. Wind Farm embedded Multi-Machine Power System with FACTS Controllers

a) With SVC Controller

When the SVC Controller is introduced in the system, the reactive power is absorbed by the system after the clearance of the fault is much less when compared to the system without FACTS controllers.

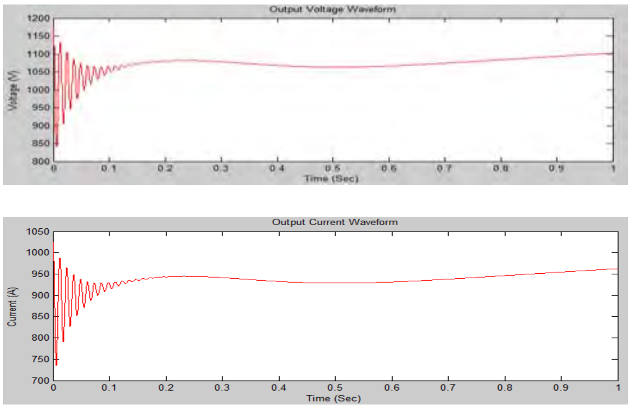

Fig 6: Output Waveform of the Wind Farm Embedded Multi-Machine Power System with SVC

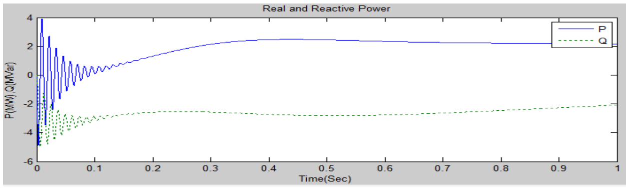

Fig 7: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System with SVC

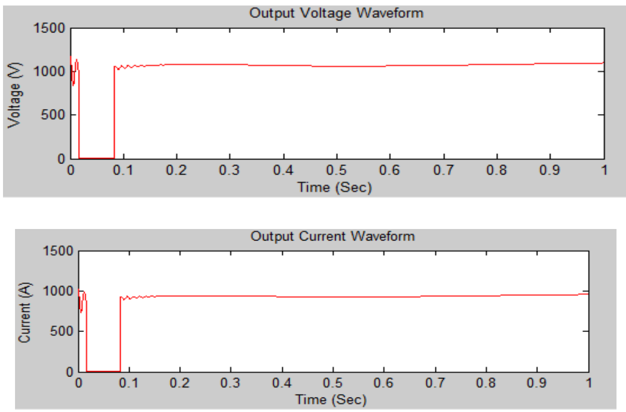

Fig 8: Output Waveform of the Wind Farm Embedded Multi-Machine Power System with SVC (with fault)

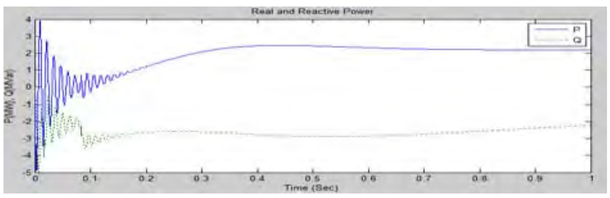

Fig 9: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System with SVC (with fault)

B. With STATCOM Controller

When the STATCOM controller is introduced in the system, the reactive power has been injected to the grid. It has boosted the output voltage and current in the system soon after the clearance of the fault. The real and reactive power losses are also much less hence the power quality has improved in multi-machine power system.

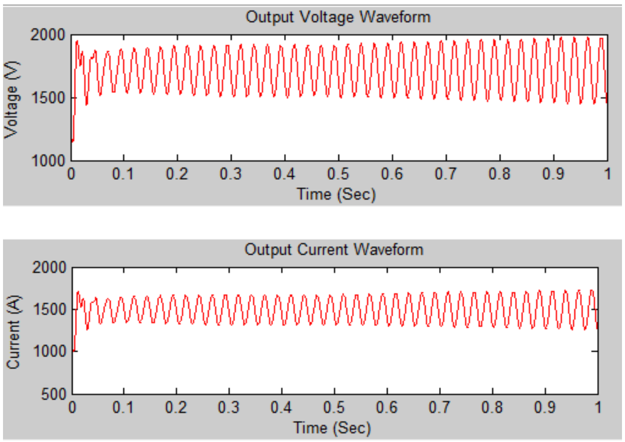

Fig 10: Output Waveform of the Wind Farm Embedded Multi-Machine Power System with STATCOM

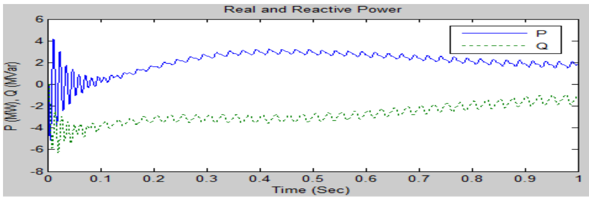

Fig 11: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System with STATCOM

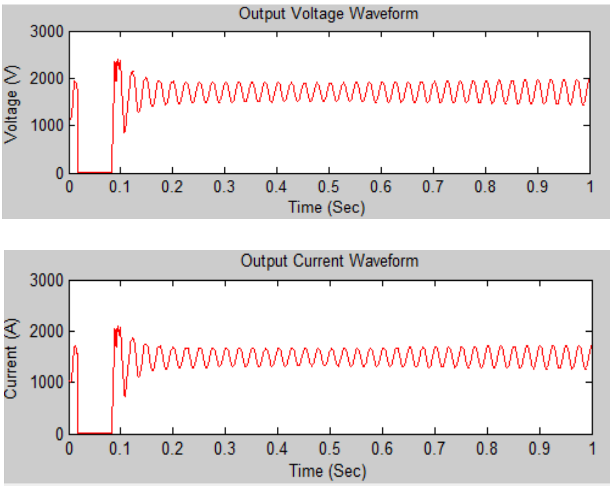

Fig 12: Output Waveform of the Wind Farm Embedded Multi-Machine Power System with STATCOM (with fault)

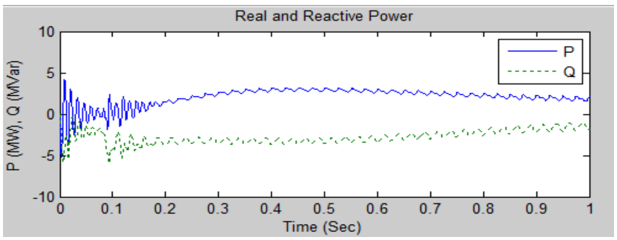

Fig 13: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System with STATCOM (with fault)

C. With UPFC Controller

At the instant of clearing, the reactive power drop is less compared to SVC Controller. Before the introduction of the fault, the UPFC has acted well, by injecting or absorbing the reactive power based on the system.

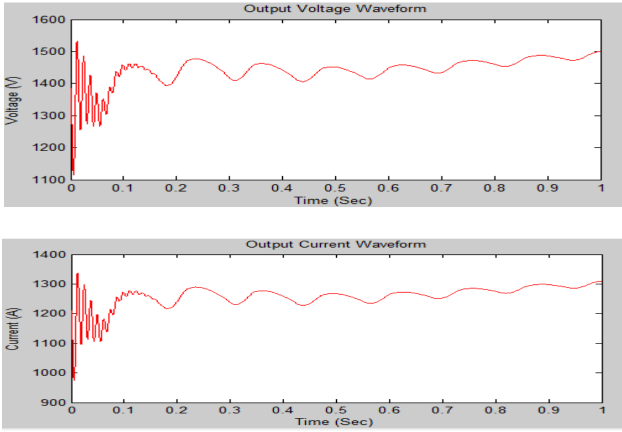

Fig 14: Output Waveform of the Wind Farm Embedded Multi-Machine Power System with UPFC

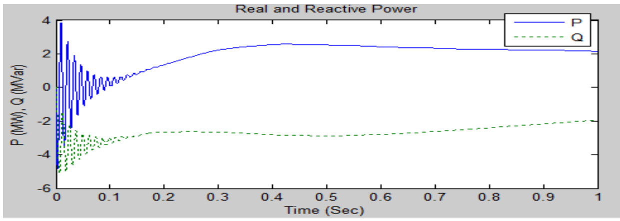

Fig 15: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System with UPFC

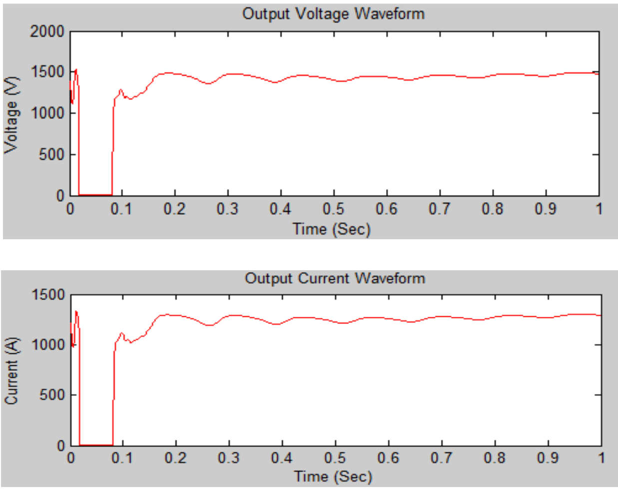

Fig 16: Output Waveform of the Wind Farm Embedded Multi-Machine Power System with UPFC (with fault)

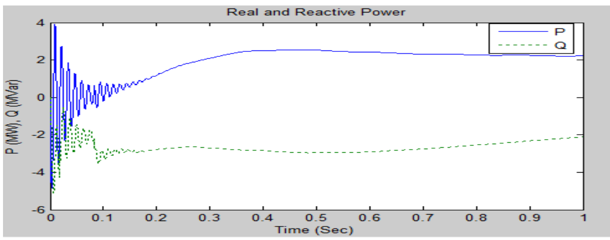

Fig 17: Real and Reactive Power Output of the Wind Farm Embedded Multi-Machine Power System with UPFC (with fault)

Normally, at the clearing instant of a fault and afterward, transients which occur due to the reactive power loss will result in significant stresses for the wind turbine mechanical system and may have effects which are harmful on the lifetime of sensitive components. Here the FACTS controllers are used when a three-phase grid fault is introduced in the system. Hence these FACTS controllers subsequently reduce the power losses after the clearance of the fault which improves power quality and in turn maintain stability in the system.

TABLE II – VOLTAGES AND CURRENTS VALUE DURING FAULT CONDITION

Various FACTS Devices	***Without Fault***		***3-Phase Fault***	
	V_{ph}	I_{ph}	V_{ph}	I_{ph}
System without any FACTS devices	1089	951.2	1083	945.9
SVC	1102	962.5	1096	957.1
STATCOM	1472	1285	1980	1729
UPFC	1500	1310	1480	1292

The STATCOM controller shows the best results comparing all other FACTS devices. It is preferred as it can provide sufficient voltage improvement for the system under consideration when compared to the other FACTS controllers used.

VI. CONCLUSION

Among all the FACTS controllers considered, even though UPFC is superior, due to economical reasons STATCOM is preferred as it can provide sufficient voltage improvement for the system under consideration. Thus the stability of the wind farm embedded multi-machine power system can be improved by using STATCOM, thereby enhancing the voltage profile and in turn improves the stability of the system.

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