IJMTST
Volume: 2 | Issue: 06 | June 2016 | ISSN: 2455-3778

Effect of TCSC Device on Voltage Stability

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ABSTRACT

The influence of series Flexible AC Transmission Systems (FACTS) device namely, Thyristor-Controlled Series Capacitors (TCSC) on the steady state voltage stability is the main objective of this paper. The Line stability Index LSI under excepted lines outage contingencies is used to identify the critical line which is considered as the best location for TCSC. A modal analysis is used to define the weakest bus of the studied system. The FACTS device is implemented and included into the Newton-Raphson power flow algorithm, and the control function is formulated to achieve the voltage stability enhancement goal. The analysis is preformed on standard IEEE 30 bus system. The proposed scheme are tested under different loading conditions and different nonlinear voltage dependent loads. The simulation results demonstrate the feasibility and effectiveness of the device and the proposed algorithm.

KEYWORDS: *voltage stability; TCSC; FACTS; voltage dependent load*

I. INTRODUCTION

The utilities interest about the voltage instability and voltage collapse problems increase due to structural changes in the electrical sector, such as those caused by privatization and deregulation, modification of the network topology, as well as ever increasing in load demands brought by economic and environmental pressures that led the power systems to operate near its stability limits. Several blackouts are reported in many countries relate to voltage stability problem [1]. As an example, there are six blackouts during six weeks affecting millions of people in US, Sweden, UK, and Denmark [2].

Generally, voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of the power system. Voltage collapse may be a possible outcome of voltage instability, which is defined as the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system [3].

A large number of researchers have been studied the voltage stability problem. Their attention has resulted with a numerous number of papers, books, and reports being published. Most of these are reported in the extensive bibliography [4].

The voltage instability may be classified into transient and steady state, the latest is the main concern in this paper. Steady state voltage stability or Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load [5].

Many of measures used to prevent voltage instability [6] such as, (i) Placement of series and shunt capacitors, (ii) Generation rescheduling, (iii) Installation of synchronous condensers, (iv) Under-Voltage load shedding, (v) Blocking of Tap-Changer under reverse operation, (vi) Placement of FACTS controllers. The last method is considered in this study.

FACTS is a terminology that embrace a wide range of power electronics controllers. These devices use no delay and high current power electronic devices available today for safe and accurate responses. They are able to control the parameters such as voltage magnitudes and their angles, line impedances, active and reactive power flows [7].

There are many types of FACTS such as, Superconducting magnetic energy storage (SMES), Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Capacitor (TCSC), Interline Power Flow Controller (IPFC), and Unified Power Flow controller (UPFC).

TCSC is considered in this paper to enhance steady state voltage stability by incorporate the device into the Newton-Raphson process under different types of voltage dependent loads.

The rest of this paper is structured as follows. In section II, the concept of the steady state voltage stability model is introduced. The structure and operation principles of TCSC is presented in section III. In section IV, the detailed static voltage stability model of TCSC is described. The mathematical model of the voltage dependent loads is explained in section V. In section VI the proposed methodology for the best placement of TCSC is considered. The results obtained for the test system is given and discussed in Section VII. Finally, Section VIII contains the conclusion.

II. VOLTAGE STABILITY

The steady state (static) analysis methods mainly depend on the steady state model, such as power flow model or a linearized dynamic model described by the steady state operation. These methods [8-10] can be divided into:

1. Load flow feasibility methods, which depend on the existence of an acceptable voltage profile across the network. This approach is concerned with the maximum power transfer capability of the network or the existence of a solved load flow case. There are many criteria proposed under this approach. Some of these criteria are the following:

- The reactive power capability (Q-V curve).
- Maximum power transfer limit (P-V curve).
- Voltage stability proximity index (VSI) or the load flow feasibility index (LFF index).

2. Steady state stability methods, which test the existence of a stable equilibrium operating point of the power system. Some of the criteria proposed under this approach are:

- Eigenvalues of linearized dynamic equations.
- Singular value of Jacobian matrix (SVJ).
- Sensitivity matrices.

The maximum power transfer limit (P-V curve) method is used here as a measure for voltage stability. The procedures used to study the influence of TCSC on the static voltage stability begin with the power flow as the first step.

The power flow model is used to study steady state voltage stability since the power flow equation yield adequate results, as singularities in related power flow Jacobian can be associated with actual singular bifurcation of the corresponding dynamical system [11].

The Newton-Raphson power flow equation represented by:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = J \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}$$

The power flow model for voltage stability analysis is represented by:

$$F(x,\lambda) = \begin{bmatrix} \Delta P(x,\lambda) \\ \Delta Q(x,\lambda) \end{bmatrix} = 0$$

where $F(x,\lambda)$ is power flow equation and λ is Loading Factor (LF) or system load change that drives the system to collapse in the following way:

$$\begin{aligned} P_{D,i} &= \lambda_{P,i} P_{D0,i} \\ Q_{D,i} &= \lambda_{Q,i} Q_{D0,i} \end{aligned} \qquad (3)$$

where $P_{D0,i}$ and $Q_{D0,i}$ represent the initial active and reactive loads at bus i and constants λ_{Pi} and λ_{Qi} respectively represent the active and reactive load increase direction of bus i.

III. STRUCTURE AND OPERATION PRINCIPLE OF TCSC

Thyristor controlled series compensator (TCSC) is one of the most popular FACTS controllers, which allows rapid and continuous modulation of the transmission line impedance [12]. TCSC vary the electrical length of the compensated transmission line which enables it to be used to provide fast active power flow regulation [7]. It is also, provides powerful means of controlling and increasing power transfer level of a system by varying the apparent impedance of a specific transmission line [13].

The basic structure of TCSC is a thyristor controlled reactor (TCR) connected in parallel with a capacitor as shown in Fig. 1

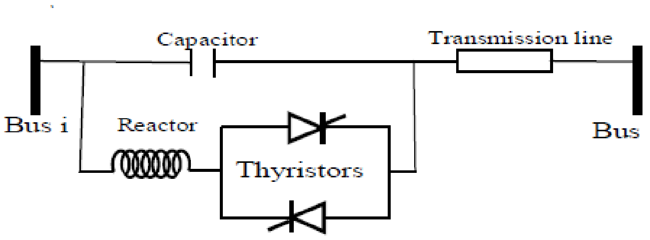

Fig 1 Schematic diagram of TCSC between bus *i* and bus j

The impedance characteristics curve of a TCSC device is shown in Fig. 2, that is drawn between effective reactance of TCSC and firing angle α [14,15].

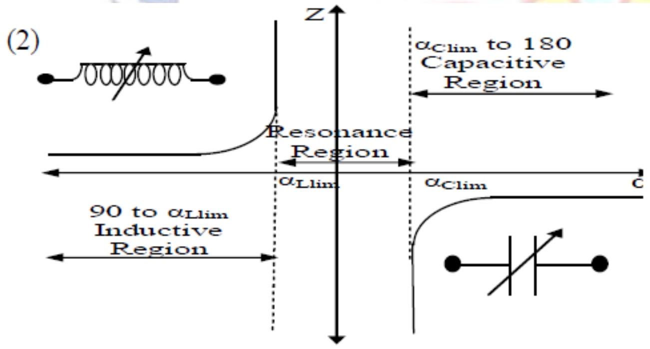

Figure 2. Impedance characteristics curve of a TCSC.

Impedance characteristics of TCSC shows, both capacitive and inductive region are possible through varying firing angle (α) as follows:

$90 < \alpha < \alpha_{Llim}$ Inductive region

$\alpha_{Llim} < \alpha < \alpha_{Clim}$ Capacitive region

$\alpha_{Clim} < \alpha < 180$ Resonance region

IV. MODELING OF TCSC CONTROLLER FOR STATIC VOLTAGE STABILITY

For static applications, FACTS devices can be modeled by power injection models (PIM) [16]. The injection model describes FACTS as devices that inject a certain amount of active and reactive power to a node, so that a FACTS device is represented as PQ elements. The advantages of the PIM are that it does not destroy the symmetrical structure of the admittance matrix and allows efficient and convenient integration of FACTS devices into existing power system analytical tools [17].

Fig. 3 shows a model of transmission line with a TCSC connected between buses *k* and *m*. During a steady state, the TCSC can be considered as a reactance $-jX_{TCSC}$. The controllable reactance X_{TCSC} is directly used as the control variable in the power flow equations.

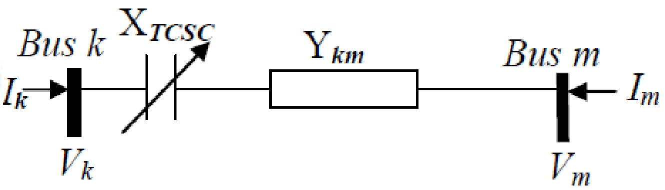

Figure 3. Modeling of transmission line with TCSC.

The current through the line after inserting TCSC is obtained by

$$I_{km} = (V_k - V_m)/[R_{km} + j(X_{km} - X_{Tcsc})]$$

The series capacitor is initially represented as a current dependent voltage source, which is later transformed into a current source Is in parallel with the line [18] where,

$$I_s = -jX_{Tcsc} I_{km} / (R_{km} + jX_{km})$$

The corresponding power injection model of the TCSC incorporated within the transmission line is

shown in Fig. 4 The injected powers S_k^F and S_m^F are defined by :

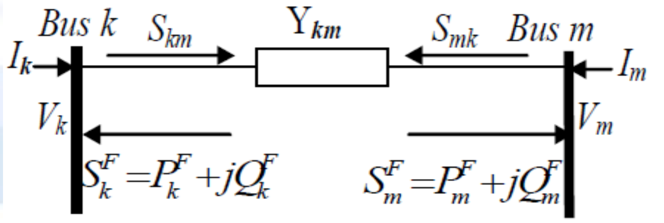

Figure 4. TCSC injection model.

$$S_k^F = V_k(-I_s)^* = V_k\left(\frac{jX_{Tcsc}}{R_{km} + jX_{km}} \frac{V_k - V_m}{R_{km} + j(X_{km} - X_{Tcsc})}\right)^* \quad (6)$$

$$S_m^F = V_m(I_s)^* = V_m\left(\frac{-jX_{Tcsc}}{R_{km} + jX_{km}} \frac{V_k - V_m}{R_{km} + j(X_{km} - X_{Tcsc})}\right)^* \quad (7)$$

The real and reactive power injections due to the series capacitor of TCSC at buses *k* and *m* are given by (8) to (11) [19]:

$$P_k^F = V_k^2 G_{kk}^F - V_k V_m [G_{km}^F \cos\delta_{km} + B_{km}^F \sin\delta_{km}] \quad (8)$$

$$Q_k^F = -V_k^2 B_{kk}^F - V_k V_m [G_{km}^F \sin\delta_{km} - B_{km}^F \cos\delta_{km}] \quad (9)$$

$$P_m^F = V_m^2 G_{mm}^F - V_k V_m [G_{km}^F \cos\delta_{km} + B_{km}^F \sin\delta_{km}] \quad (10)$$

$$Q_m^F = -V_m^2 B_{mm}^F - V_k V_m [G_{km}^F \sin\delta_{km} - B_{km}^F \cos\delta_{km}] \quad (11)$$

To implement voltage control function model of TCSC in Newton-Raphson algorithm, there are two model of TCSC. In the first one, X_{Tcsc} is considered as (5)

the state variable, Where the series reactance is adjusted automatically, within limits, to satisfy a specified amount of active power flows through it. In the second model TCSC firing angle is chosen to be the state variable in the Newton–Raphson power flow solution. Where TCSC reactance–firing-angle characteristic, given in the form of a nonlinear relation. The first model is used in this study.

To improve the static voltage stability, The bus voltage control mode is used , So the bus voltage control constraint of bus k is given by

$$VC = V_k - V_k^{sp} = 0 \qquad (12)$$

V. SIMULATION RESULTS

Voltage stability enhancement using the proposed TCSC FACTS device is done through the simulation of IEEE 30- bus test system (shown in Fig. 6). Studied system data is obtained from [26]. All the results are produced by programs developed in MATLAB® software package.

The system consists of 6 machine, 30 bus, and 41 lines. Bus 1 is considered as slack bus, while 5 nodes

as PV buses and other buses as PQ buses. For all cases, the convergence tolerance is 1e^{-12} p.u. and system base is 100 MVA

As explained in the previous sections LSI under line outage analysis, and modal analysis are used to identify the best location of the TCSC, and the weakest bus required to form the voltage control function,(31) then the TCSC device is incorporated to the system. The effect of the system without and with TCSC is studied under different loading conditions and different load types to investigate the ability of the FACTS device to enhance static voltage stability of the studied system.

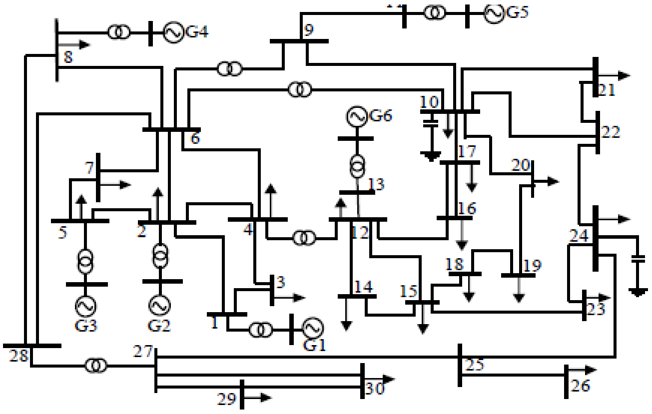

Figure 6. The IEEE 30-bus power system.

A. Best Location for TCSC Placement

To define the appropriate placement of TCSC, firstly the base load flow study is carried out, the LSI is computed and ranked, and the most ten severe lines according to LSI values are recorded in Table I. Then the lines outages are simulated and the LSI are computed for each line outage case and the highest LSI value for each case is extracted, and the most serious outage contingency are identified and listed in Table II. The outages of L38 and L39 give non convergence results "NC" and LSI greater than one which mean that these lines cases the system unstable. From the two tables, it is appeared that L38, L39, and L20 are the common lines between the critical lines lists in the base case and in the line outages contingency cases. And the line L38 (the line connecting buses 27-30) is the most critical line which have the highest LSI value. Further more investigating the LSI values of Table II indicate that the line L38 itself has the highest LSI value under most of the lines contingencies So, the line L38 is chosen to place TCSC device.

TABLE I. THE HIGHEST RANKED LINES ACCORDING TO LSI

Line No	From -To	LSI	Rank
38	L 27-30	0.1765	1
13	L 9-11	0.1722	2
39	L 29-30	0.1378	3
32	L 23-24	0.1159	4
8	L 5-7	0.0907	5
1	L 1-2	0.0904	6
20	L 14-15	0.0867	7
31	L 22-24	0.0864	8
16	L 12-13	0.0822	9
27	L 10-21	0.0752	10

B. Simulation Results With Effect of TCSC Using Linear Loads

To investigate the effect of the TCSC device suing linear loads (P-constant load), PV curves of the critical buses 30, 29, and 26 without and with TCSC (TCSC at line 27-30) are shown in Fig. 10 to Fig. 12. Fig. 10 indicates that the device succeed to fix the voltage of the most critical bus 30 to the objective value (1 p.u.), despite the increasing of the loading factor to 1.4. Also, Fig.11 and Fig. 12 show an improvement in the voltage profiles in buses 29 and 26. So, all the results are shown that the voltage profiles are enhanced and consequently the voltage stability margin of the studied system are improved due to using TCSC

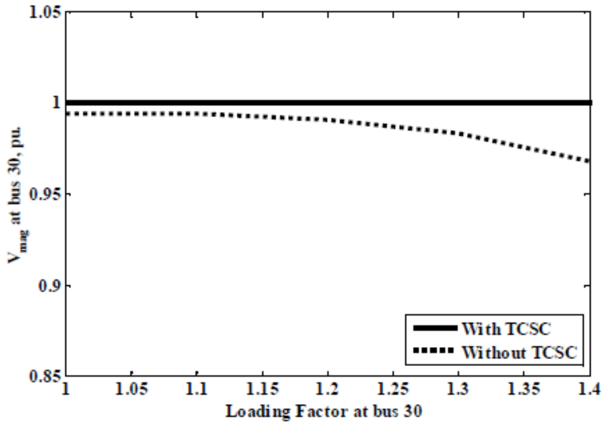

Figure 10. P-V curve of bus 30 without and with TCSC

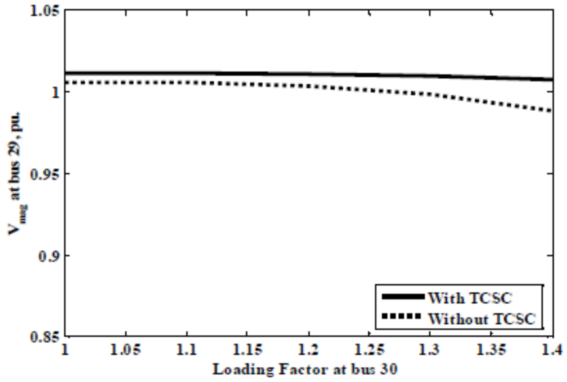

Figure 11. P-V curve of bus 29 without and with TCSC.

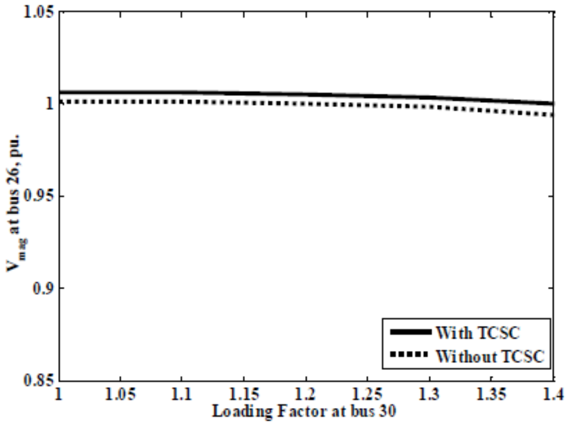

Figure 12. P-V curve of bus 26 without and with TCSC

C. Simulation Results with Effect of TCSC using Voltage Dependent Loads

To explore the effect of the TCSC device on the proposed system under different nonlinear voltage dependent loads, PV curves of the buses 26, 29, and 30 without and with TCSC are plotted in Fig. 13 to Fig. 21. Figures are zoomed when required to explain the case. Also, the loading factor are changed according to case stability.

Figures 13 to 15 simulate the change in voltage magnitude of the three buses in the studied system without TCSC under constant current (CI), constant impedance (CZ), and constant power (CP) loads. These figures indicate that the voltage magnitude are decreased to undesirable levels that lead to voltage collapse.

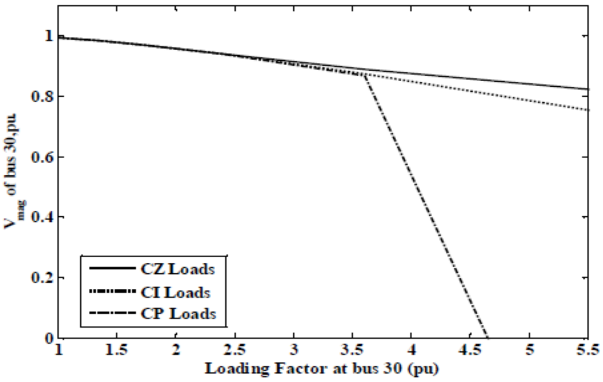

Figure 13. P-V curve of bus 30 for different load types

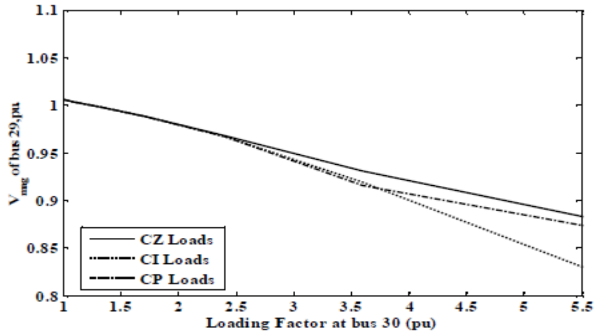

Figure 14. P-V curve of bus 29 for different load types

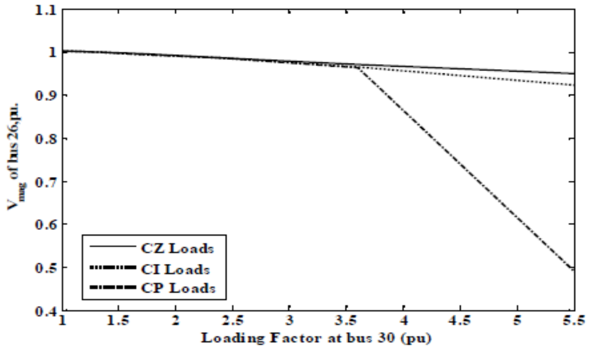

Figure 15. P-V curve of bus 26 for different load types

In figures 16 to 18 a comparison between the system with TCSC and without TCSC using constant current loads are depicted. Also, In figures 19 to 21 the same process is done, using constant impedance load types (constant power case are studied as linear load). In figures 12, 18 and 21 the TCSC has a small effect on bus 26 this is because of bus 26 is not connected directly to bus 30 that is connected to TCSC this means that the redistribution of reactive powers by the device has not a large effect of this bus. In general TCSC shows a good performance and enhance the voltage stability margin of the system.

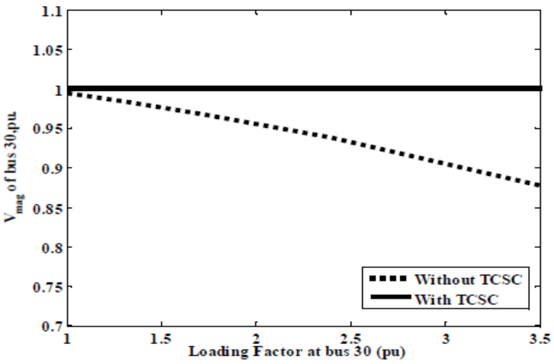

Figure 16. P-V curve of bus 30 for constant current load

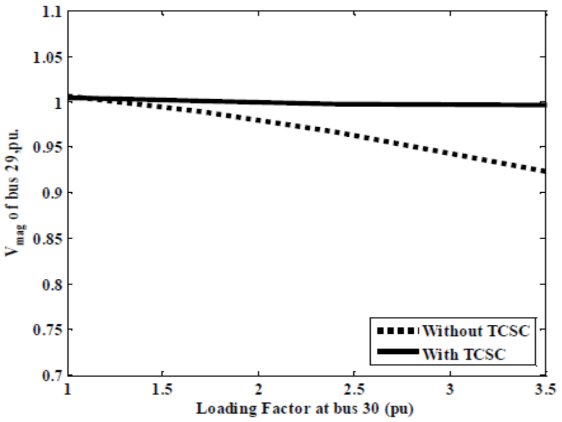

Figure 17. P-V curve of bus 29 for constant current load

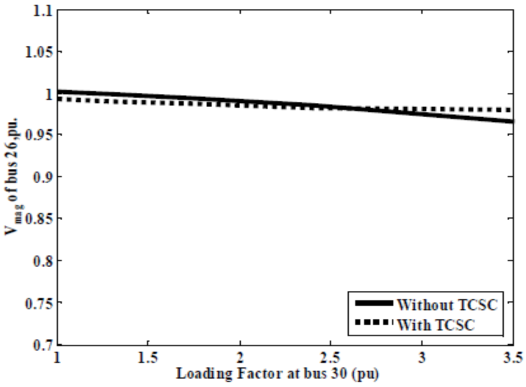

Figure 18. P-V curve of bus 26 for constant current load

VI. CONCLUSION

In this paper the influence of TCSC on steady state voltage stability was investigated. Detailed steady state model of FACTS device was presented focusing on the inclusion of the devices into the power flow analysis process. A novel techniques for selecting best placement of the device and to form the voltage control function were proposed. The studied system was tested under different loading conditions and different linear and nonlinear load types. The device proved their ability to enhance voltage stability margin.

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