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Control of over currents and over voltages of the shunt capacitor banks

***Abstract**. The transition state, which, happened at the commutation of simple and multiple condensers batteries provokes the generation of dynamic disturbances (over currents and over voltages). For successful compensation these perturbations must be kept within accepted limits. The present work describes and establishes a relationship of the transients and the complex interaction between shunt capacitor banks, source and the load. In order to keep transients under control, the overvoltage factor (km) must be kept nearer to one and must be not superior to unity.*

***Streszczenie.** Stan przejściowy, który nastąpił przy komutacji baterii prostych i wielokrotnych kondensatorów, powoduje powstawanie zaburzeń dynamicznych (przetężenia i przepięcia). Dla skutecznej kompensacji te perturbacje muszą być utrzymywane w akceptowanych granicach. W niniejszej pracy opisano i ustalono związek stanów nieustalonych oraz złożoną interakcję między bateriami kondensatorów bocznikowych, źródłem i obciążeniem. Aby utrzymać stany nieustalone pod kontrolą, współczynnik przepięcia (km) musi być bliższy jedności i nie może być wyższy od jedności.(**Kontrola nadprądów i przepięć baterii kondensatorów bocznikowych**)*

Keywords: Transient response, commutation, capacitor banks, dynamic disturbances.
Słowa kluczowe: Odpowiedź przejściowa, komutacja, baterie kondensatorów, zaburzenia dynamiczne.

Introduction

The optimization of the electrical system can be enhanced by reactive power compensation. Shunt capacitor banks (SCBs) are widely used for reactive power compensation and bus voltage regulation [1] .Capacitor banks must be energized and de-energized (switched in and switched out) several times in accordance with the behavior of the system load profile, where loads fluctuate rapidly. These banks generate a switching transient inrush current when they are switched on [2]. The transition between stationary states together with a variable propagation of the frequency generates a huge amount of energy exchange between the system components. For the control of the over-voltages and dynamic over-currents generated during commutation of condensers batteries it is necessary to determine the optimal characteristics from their respective quality indices, in other words, establishing a conditional relationship from the maximum transient values of the voltage and of the current [3]. In this work, a multiple stages network model is considered.

Model description

A multiple stages network model is considered as shown in Fig. 1. In general, the node of commutation (NC) of the compensators can be situated in various positions in the network hierarchy. The transient parameters of the capacitor banks in the node can be obtained easily by transcending the general network into a simple model made up of three element blocks. Which, are composed of equivalent networks with E_0 is the source outputting through a link impedance $Z_s=r_s+jx_s$ and the equivalent complex load given by the impedance Z_L as shown in Fig.1 (b). The model thus obtained can be still reduced to a more convenient form Fig.1 (c), with the help of the complex factors K_{1E} and K_1, as follows:

$$(1)\qquad \begin{aligned} E &= E_{eq} = (k_{1E}^{'} + jk_{1E}^{"})E_0 = \dot{K}_{1E}E_0 \\ Z &= Z_{eq.s} = (k_1^{'} + jk_1^{"})x_s = \dot{K}_1 x_s \end{aligned}$$

With,

$$k_1^{'} = \frac{tk_{sx}(1+t_s^2)+t_s(1+t^2)}{(t_s+tk_{sx})^2+t^2t_s^2(1+k_{sx})^2}$$

$$k_1^{"} = \frac{t^2k_{sx}(1+t_s^2)+t_s^2(1+t^2)}{(t_s+tk_{sx})^2+t^2t_s^2(1+k_{sx})^2}$$

$$\dot{K}_{1E} = \frac{t_s}{1+jt_s}\dot{K}_1$$

$$k_{1E}^{'} = \frac{k_1^{'}+t_sk_1^{"}}{1+t_s^2}$$

$$k_{1E}^{"} = \frac{k_1^{"}-t_sk_1^{'}}{1+t_s^2}$$

The switching of the BC engages the elements of the node in a transient interaction where the evolution of the voltage obeys to the differential equation,

$$(2)\qquad e(t) = LC\frac{d^2u_c}{dt^2} + RC\frac{du_c}{dt} + u_c(t)$$

During the switching of the capacitor banks, the transient response of the voltage, for the most constraining case, is described by the following expression [4], [5]:

$$(3)\qquad k_u(t) = \sin(\omega t+\psi-\phi) + e^{-\delta t}(A_u^*\sin\omega_0 t + B_u^*\cos\omega_0 t)$$

With,

$$A_u^* = \frac{\omega_0^*\left[U_0^* - \sin(\psi-\phi)\right]\cos\alpha - \sin\alpha\cos(\psi-\alpha)}{\omega_0^*\sin\alpha}$$

$$B_u^* = U_0^* - \sin(\psi-\phi)$$

Where, $k_u(t)$ is the instantaneous value of the p.u voltage of the node considered, $\delta = R/2L$ defines the damping of the free mode, L, R and C are the variable parameters of the studied model corresponding to different levels of the network hierarchy; ω_0, ω pulsations, respectively, of the free and forced exchanges; $\omega^*_0 = \omega_0/\omega$ the p.u free pulsation, $\alpha = \text{arctg}(\omega/\delta)$, $U^*_0 = -1, 0, 1$ are various initial voltage of capacitor banks and $\psi = \varphi, \varphi+\pi, \varphi \pm \pi/2$ are the various characteristic angles of commutation of the capacitor banks.

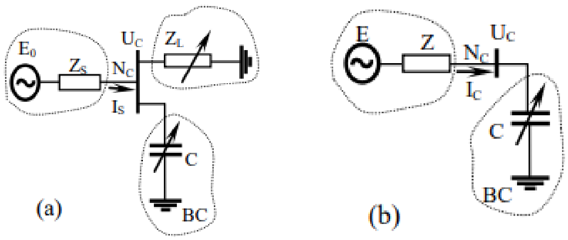


Fig. 1. (a): block elements of the node, (b): reduced form.

The damping factor δ depends only on the electric parameters of the equivalent circuit.

$$\delta = \frac{\omega}{2}\left(\frac{t(1+t_s^2)+k_{L,s}}{1+t_s^2+t_s k_{L,s}}\right) \tag{4}$$

Where

$$k_{L,s} = \frac{x_L}{r_s} = n\sqrt{(1+t^2)(1+t_s{}^2)} \quad n = \frac{S_{sc}}{S_L}$$

The analysis of the relation (4) enables the evaluation of the variations and the intensity of the damping factor versus the position of the node in the system hierarchy.

The damping factor is calculated for different values of reactive power, according to the relation S_{sc}/S_L. For enhanced ratios of the installed powers of the node, the effect of damping is more important for lower values of the ratio t_s. At the same time and in the same direction, the relationship between active and reactive power becomes less important. These characteristics can be explained by the curves in Fig. 2; the damping factor is more important for nodes located in low voltage levels.

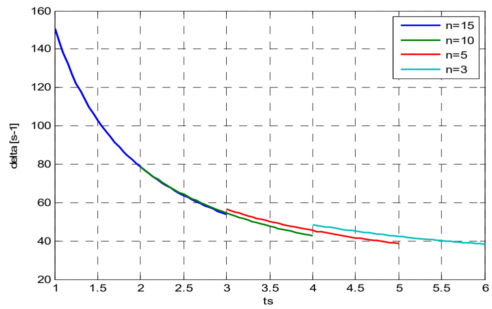
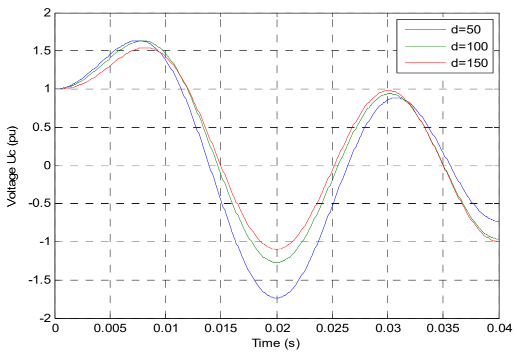


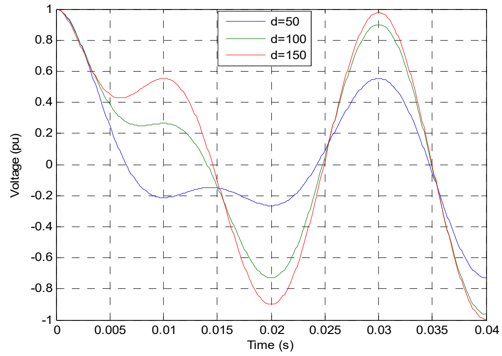
Fig. 2. Damping factor versus the ratio t_S for different values of S_{sc}/S_L.

Condition of overvoltage reduction

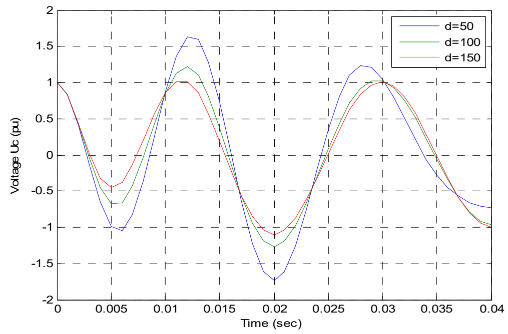
The expression (3) defines various transient response for different descriptive parameters (ψ, δ, ω*0, U0). In the Fig. 3, the transient response for three cases of the damping factor; δ=50,100 and 150 s-1 in the figure the factor delta is denoted by d. The others parameters U_0*=1, ψ = φ-π/2 and three values of free pulsation ω^*_0 .



(a)



(b)



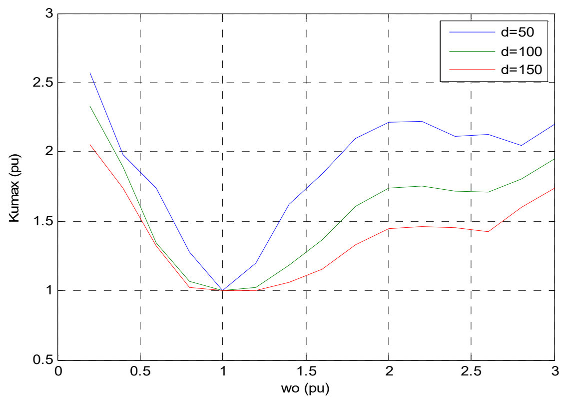
(c)

Fig. 3. Transient response of the voltage U_c : (a): $\omega^*_0 = 0.5$, (b): $\omega^*_0 = 1$, (c): $\omega^*_0 = 1.5$

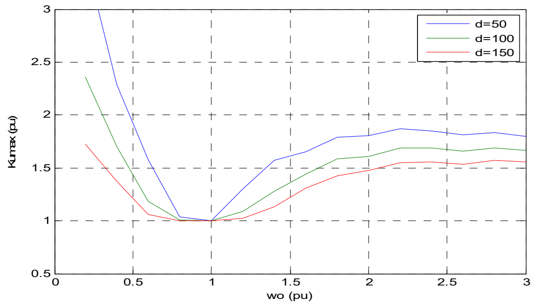
The recording of the maximum overvoltage value on each response allows the definition of the maximum values ku.max (ω^*_0) for different values of δ, ψ and U^*_0, are presented in Fig. 4. For the values of $\omega^*_0 > 1$, the factor $k_{u.max}$ increases with the reduction of δ and this increase is enhanced when $U^*_0 = \pm 1$. This gap is larger when ψ = φ-π/2 (ψ being the initial phase of E and φ is the phase shifting of the current of the capacitor banks). This means, at the instant when the forced voltage $u_{cf}(t)$ of the node changes alternatively. When $\omega^*_0 < 1$, the voltage is amplified for ψ = φ+π. The curves thus represented in Fig. 4 illustrate an interesting result. Indeed, it can be noted that, whatever the value of the parameters ψ, δ and U_0, for $\omega^*_0 = 1$; the following relation can be achieved:

$$k_{u.\max} = k_{u.\max(\min)} = 1 \tag{5}$$

Thus, in order to decrease $k_{u.max}$, the value ω^*_0 must be closer to the unity.



(a)



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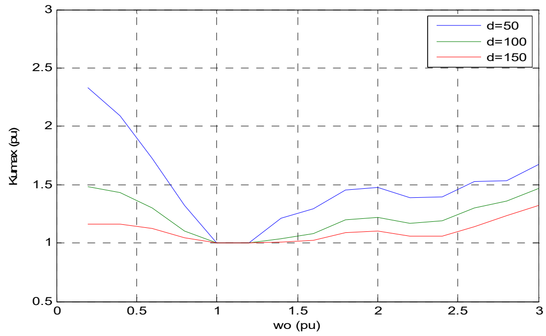

(c)

Fig. 4. Optimal transient characteristics. $k_{u.max}$ (ω^*_0) for $U_0^*= \pm 1$: (a): $\psi = \varphi$-π/2, (b): $\psi = \varphi$ +π, (c): $\psi = \varphi$.

The above result is very well represented in Fig. 5-8. The curves shows the variation of the instantaneous values of the voltage and of the current (k_u and k_i) of capacitor banks versus the pulsation ω^*_0 of the free transient mode. Independently of the parameters considered, these charts observe a narrowing in the limit $-1 \le \Delta k_{u,i} \le 1$ in the vicinity of $\omega^*_0 = 1$. On both sides of this zone, the circuit can be in a state of overvoltage and of over-current.

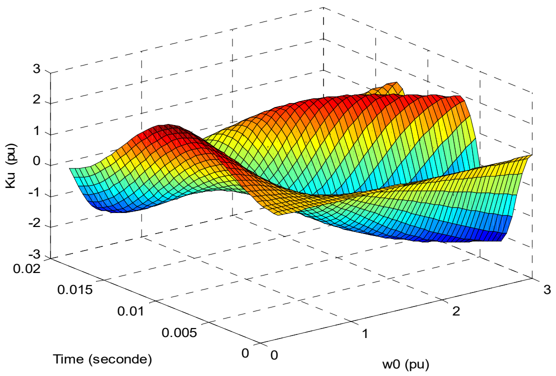

Fig. 5. The transient evolution of the voltage k_u; U_0^*=1 and $\psi = \varphi$-π/2.

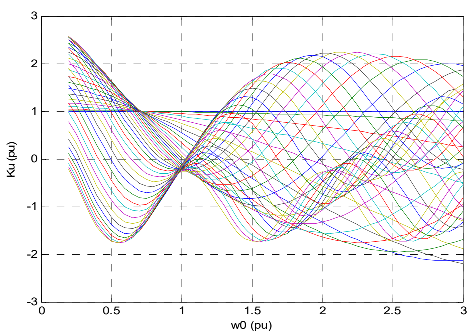

Fig. 6. The transient voltage. k_u (ω^*_0)

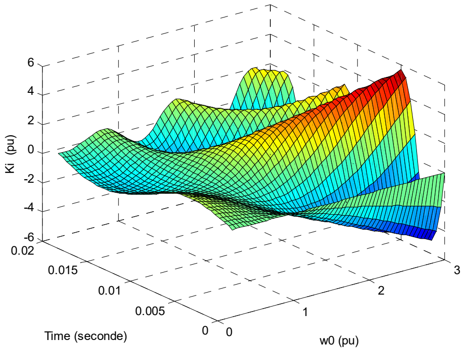

Fig. 7 The evolution of the transient current k_i ; U_0^*=1 and $\psi = \varphi$-π/2.

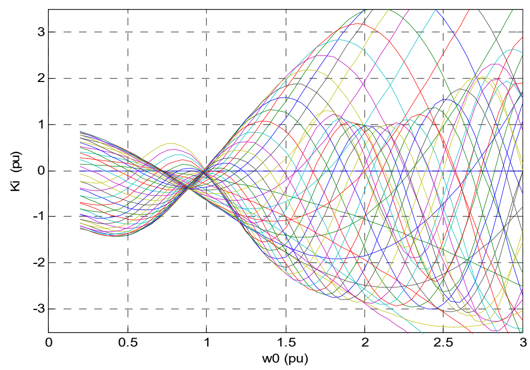

Fig.8. The transient current. ki (ω^*_0).

Optimal relation between interactive parameters

From the relation (5) it is possible to determine the optimal values of the interactive parameters of the model. Indeed, the resolution of the differential equation in transient mode of the reduced model Fig.1 (b), gives the following expression [4]:

$$\omega_0^2 = \frac{1}{LC} - \frac{R^2}{4L^2} \tag{6}$$

The optimal values of the capacitors for $\omega_0^* = 1$ can be expressed in the p.u system as follows:

$$C^*_{(1)} = \frac{L^*}{AL^{*2} + 1} \tag{7}$$

Where, C*(1) is the p. u. value of the optimal capacitor. The p.u. values given are those corresponding to a basic model of parameters L_0, R_0, C_0 for which the condition of periodicity of the transient mode is met $C^* < C^*_{0n} = L^*$; $C^*_{0n} = C_{0n}/C_0$, defines the limiting capacitor corresponding to the condition where $C_0 = \dfrac{4L_0}{2R_0^2}$;

$L^* = L/L_0$ expresses the variation of inductance and $A = \dfrac{\omega^2}{\delta_0^2}$ gives an average indication on the position of the node in the network.

The optimal impedance of the model takes the following form:

$$Z^{*2}_{(1)} = Z^{*2}_{\min} + \frac{1}{(A+1)^2 L^{*2}} \tag{8}$$

where, $Z_{\min}^{*2} = \dfrac{R_0^2}{Z_0^2}$ is the impedance of resonance of the model and Z_0 - impedance of the basic model. The values of the capacity of resonance can be obtained from the expression of the impedance of the model,

$$Z^{*2} = Z_{\min}^{*2} + \frac{\left(AL^{*}C^{*} - 1\right)^2}{(A+1)C^{*}}$$

for,

$$AL^{*}C_{(r)}^{*} - 1 = 0$$

so,

$$(9) \quad C_{(r)}^{*} = \frac{1}{AL^{*}}$$

The expressions (7), (8) and (9) are graphically represented on Fig.9 together with the characteristic of field variations are also delimited, according to C and L, of the free pulsation. The analysis of the characteristics thus obtained allows the following deductions:
For the interval of the optimal capacity variation $C^*_{(1)}$,

$$0 < C_{(1)}^{*} \le C_{(1)m}^{*} = \frac{1}{2\sqrt{A}}$$

Two intervals of inductance characteristics variation can be distinguished:

$L^{*} \ge L_{(m)}^{*} = \dfrac{1}{\sqrt{A}}$ and $0 < L^{*} \le L_{(m)}^{*} = \dfrac{1}{\sqrt{A}}$

where, $L^*_{(m)}$ - inductance of the model corresponding to the maximum value $C_{(1)m}$ of the optimal capacity $C_{(1)}$.
In the first interval the increase of L*, in accordance with (5, 6 and 7), will push $C^*_{(r)}$ towards $C^*_{(1)}$ and consequently, $Z^*_{(1)}$ and Z towards $Z_{min} = R_0$, where the transient over-currents would be considerable. In the second interval, the reduction of L* will cause $Z_{(1)}$ to increase considerably pushing down the values of the over-currents. For this interval, the damping δ increases and therefore, diminishes the time of the transient mode. The factor A is defined as the ratio X/R (X = ωL) of the equivalent model, this ratio changes with the position of the node considered. So, factor A takes various values according to whether the node is at low or at high voltage.

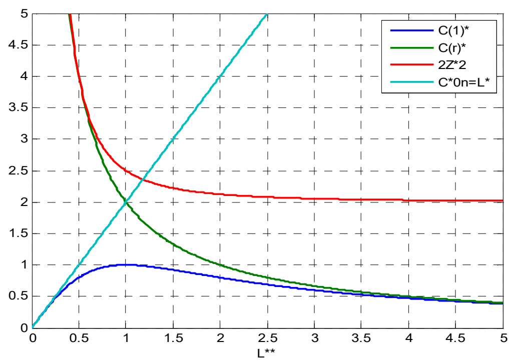

Fig. 9. Optimal parameters: $C^{**}_{(1)} = C^*_{(1)}/C^*_{(1)m}$; $L^{**} = L^*/L^*_{(m)}$ $C^{**}_{(r)} = C^*_{(r)}/C^*_{(1)m}$; $C^*_{(1)m} = 1/(2\sqrt{A})$; $L^*_{(m)} = 1/\sqrt{A}$.

Control of banks compensation

The present model (Fig. 10) is practically the same one as the preceding. The coefficient m measures indirectly the fraction of adjustment of the reactive power to be commutated only once: m = 1÷0 for the disconnection and m = 1÷2 for the connection. The maximum values of the factors of overvoltage ku.max and over-current ki.max can be controlled by the law of commutation mode of the reactive power [6]-[7]. A level of control, in this case, consists of some fractions. The instantaneous values $k_u(t)$ and $k_i(t)$ are expressed (for ψ= φ) as follows:
for the disconnection,

$$(10) \quad k_u(t) = K_{mf}^{*} \sin \omega t + e^{-\delta t} \frac{K_{L2}^{*}}{\omega_0^{*}} \sin \omega_0 t$$

$$(11) \quad k_i(t) = \frac{m}{\omega}\frac{dk_u(t)}{dt} \cong m\left(K_{mf}^{*} \cos \omega t + e^{-\delta t} K_{L2}^{*} \cos \omega_0 t\right)$$

for the connection,

$$(12) \quad k_u(t) = K_{mf}^{*} \sin \omega t + e^{-\delta t}\left[a_u \sin \omega_0 t + b_u \cos \omega_0 t\right]$$

$$(13) \quad k_i(t) = m\left\{K_{mf}^{*} \cos \omega t - e^{-\delta t}\left[a_i \sin \omega_0 t + b_i \cos \omega_0 t\right]\right\}$$

with

$$a_u = \frac{K_{L2}^{*}}{\omega_0^{*}} + \frac{(m-1)\delta U_{02}^{*}}{mk_0\omega_0} \; ; \qquad b_u = \frac{(m-1)U_{02}^{*}}{mk_0}$$

$$a_i = \frac{\delta K_{L2}^{*}}{\omega_0} + \frac{(m-1)\left(\dfrac{1}{A\omega_0^{*}} + \omega_0^{*}\right)U_{02}^{*}}{mk_0} \; ; \quad b_i = K_{L2}^{*}$$

Where, $K^*_{mf} = Z_1/(mZ)$; $K^*_{L2} = 1/m - K^*_{mf}$; $k_0 = k_1/(Z_1C_0\omega)$; k_1 is a factor defined by [4], Z_1 and Z are the impedances of the model, respectively, variation of the load without commutation and the load variation with commutation of the condensers batteries.

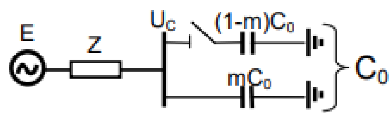

Fig. 10. Simplified model of transient mode of commutation

Figure.10 shows a representative system of the isolated switching capacitor bank for energizing an isolated capacitor bank from a predominantly inductive source [8].

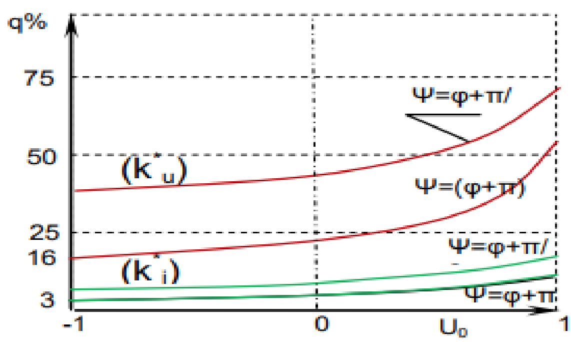

Fig.11. Characteristics of control capacitor banks for $k_{u,\,i.max} = 1.1$

The characteristics of control in Fig. 9, have been obtained from the analysis of the transient responses equations (10),(11),(13) and (14) for various phases and fractions of commutation. These give the maximum values of the fraction of the reactive power to be commutated only once (q% of the installed power) for which $k_{u,i.max}$ = 1.1. In the absence of the methods of control of the overlap angle and whatever the initial potential state of the commutated elements of the capacitor banks, the value of q% should not exceed q_{max}=3% to avoid an over-current and q_{max}=16% to avoid an overvoltage in the case of the connection.

Conclusion

The maximum factors of overvoltage and over-current observe a minimal value, independently of the damping ratio, the initial potential state of the capacitors and the phase of commutation, provided the value of the free pulsation is equal to the forced pulsation. The conduction of the transient mode under these conditions is tributary, in fact, on the adequate assessment of the free energies initially stored in the magnetic and electric fields. The transitory mode during the process of compensation of the reactive power must be controlled by the maximum factor of over-current in the case of the increase in the load and by the maximum factor of overvoltage in the case of load reduction. These conditions are reduced, in fact, to the control of the impedance. If the injected reactive power is adopted for the control; in this case, the value injected must make the compromise between the small values for which the impedance of the system is higher and the high values for which the potential energy is higher.

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