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Active compensation in a low voltage network comprises power factor correction capacitor with harmonic current producing loads

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Abstract—**In this paper, a compensation strategy for a low-voltage network comprises a power factor correction capacitor and non- linear loads connected to the same load-buss is investigated. The loads in the low- voltage network can be classified, from the harmonics point of view, into harmonic current producing loads, harmonic voltage producing loads and harmonic sensitive loads. The compensation in the low -voltage side of a power network is more reliable, efficient, economic and straightforward. The idea here stems from the fact that when applying a pollution treatment for a river, it is not practical, in all cases, to establish a treatment unit across the river. The more reliable solution is to clean and purify those outlets discharging into the river individually. If this concept could be generalized in industry, it is logical that the cost of applying the proposed compensation strategy to an industrial unit would not be comparable either to the price of the production line or to the penalties paid to authority on the long run. In the next sections, the proposed strategy will be clarified through analysis, design and simulation using a shunt active power filter.**

I. INTRODUCTION

Non-linearities were brought to the utility network with the increasing use of power semi-conductor devices in industrial control. Using these devices in power control creates serious harmonics problems. Power converters have a significant contribution in generating harmonics during switching actions. Low order harmonics usually have considerable magnitudes and diversified phase angles [1]. These harmonics are responsible for the distortion of the line voltage and lead to several adverse effects including equipment overheating, the malfunction of solid-state devices and interference with communication systems [2]. Industrial loads are the massive part of the load of any utility network. These loads are responsible for most problems of power quality [3]. Power factor correction capacitors are connected mainly to a load-buss to control and improve the displacement factor due to linear loads. However, the idea of dealing with the problem of power quality partially on a limited scale is quite convenient. In this case, the load is assumed precisely identified and accordingly, both of current and voltage profiles are predictable at the different loading conditions. In a large multi-busses power system, the loads are changing randomly each moment. Therefore, besides the well-known problems of applying compensation to such systems, the control techniques discussed in the literature were suffering from the problem of that time delay between the moment of measuring the load voltage and /or current and that of injecting the compensating current [4]. What can be called “a time-racing problem” arises here because the proper compensating current for the passed moment would not be the same for now as the load surely changes.

II. SYSTEM DESCRIPTION

An industrial load can be modeled by non-linear load connected to the mains as shown in Fig.1.

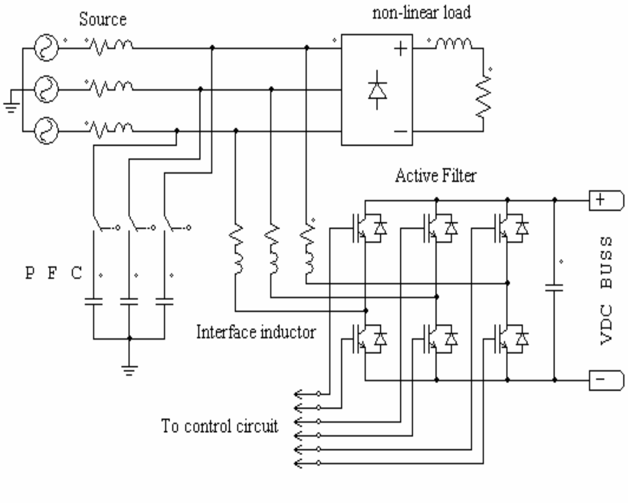

Fig. 1. System configuration.

The shunt active filter is mainly a voltage fed -inverter designed to pump a controllable reactive current into the point of common coupling via an interface inductor. The power factor correction capacitor is connected to the same buss with the shunt active filter. The non-linear load as shown is a harmonic current producing type. The bases of the IGBT power transistors are connected to the control circuit. This control circuit is a PWM modulator operates at a high frequency carrier to modulate the inverter current to track a reactive current reference signal. The idea of the current controller is based upon

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sensing the output- inverter current and comparing it to a desired reference. By a proper design of a PID controller, the inverter current can be forced to track its reference at steady state.

III. ANALYSIS

A study for compensation in a low voltage network was introduced in [5]. Taking the interactions of circuit parameters into consideration, it was shown that the optimum compensation is achieved when the following two conditions are fulfilled,

$$I_f = k\, I_{L0}\, (\omega = \omega_h) \tag{1}$$

$$\left|\frac{Z_L}{1-k}\right|_{\omega = \omega_h} >> \left|Z_s\right|_{\omega = \omega_h} \tag{2}$$

Where, (I_{L0}) is the load current, (Z_L) is the equivalent load impedance, (I_f) is the reactive current injected by the shunt active filter, (Z_s) is the equivalent source impedance including the impedance of the feeder- cable to the load, (ω_h) is the frequency of the higher dominant harmonics and (k) is the active filter gain. The optimum theoretical value of (k) is unity when $\omega=\omega_h$ but practically and due to physical limitations, it swings around 0.9 for proper design [5].

The power factor correction capacitor creates a transient voltage magnification when switched into the power system [6]. These voltage surges are dangerous for the semi-conductor switches of the active filter. On the other hand, the capacitor bank itself constitutes an upstream low- impedance path for the reactive current at steady state. The result out of this is that the condition in (2) is no longer hold. As a consequence, the input DC voltage of the inverter fluctuates severely around its nominal value and the performance of the active filter becomes unsatisfactory. To solve this problem, it is necessary to shunt a capacitor (C_f) across the terminals of the DC supply. The DC voltage across this capacitor is regulated and controlled, in a way, to regain the power balance between the active filter and the mains. Moreover, the DC voltage across (C_f) must be kept constant to provide a stable operation for the shunt active filter [7].

IV. REFERENCE CURRENT GENERATION

The instantaneous active and reactive power theory, which referred to as p-q theory, is being used successfully to design and control the active filters. Starting with Park's vector definition for voltage and current and projecting these vectors in two orthogonal stationary frame coordinates α-β, the instantaneous values of active and reactive power can be easily measured. The instantaneous active power (p) and reactive power (q) can be also solved into their fundamental components $\bar{p}$ and $\bar{q}$ and their harmonic components $\tilde{p}$ and $\tilde{q}$ respectively. These $\tilde{p}$ and $\tilde{q}$ are responsible for what so-called "the harmonic distortion power".

There are several ways to derive the p-q algorithms. This entirely depends upon the compensation strategy and the optimum power flow of the system [8]. In this paper, the two components of the reactive reference current ($i_{\alpha q}$ and $i_{\beta q}$) are extracted by online calculations. Both of the load voltage and current in a-b-c reference frame are sensed and transformed into α-β orthogonal frame. The p-q algorithm used to calculate ($i_{\alpha q}$ and $i_{\beta q}$) is:

$$\begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} = \frac{1}{\left|v_\alpha^{\,2} + v_\beta^{\,2}\right|} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix} \tag{3}$$

Where,

$$\hat{p} = -\tilde{p} + p_{av} \tag{4}$$

$$\hat{q} = -\tilde{q} \tag{5}$$

The instantaneous active power (p) and reactive power (q) are defined in α-β orthogonal frame according to the p-q theory as:

$$p = i_\alpha v_\alpha + i_\beta v_\beta = \bar{p} + \tilde{p} \tag{6}$$

$$q = v_\beta i_\alpha - v_\alpha i_\beta = \bar{q} + \tilde{q} \tag{7}$$

Two high pass filters are required to extract both of $\tilde{p}$ and $\tilde{q}$ from (p) and (q) of (6) and (7) respectively. The still-missed term in (4) is (p_{av}). This term is obtained by regulating the DC voltage across the capacitor (C_f) at the input of the inverter. The actual capacitor voltage is compared to a reference value to obtain the error signal. This error signal contains a higher- frequency component due to the high frequency switching of the inverter. After filtering out this high frequency component using a low pass filter, the error signal is fed to a P-I controller, which is the heart of the voltage loop controller. The output of this controller represents the average active power (p_{av}) that passed back to the algorithm of (3). Fig.2 shows the voltage loop controller as simulated by PSIM ®.

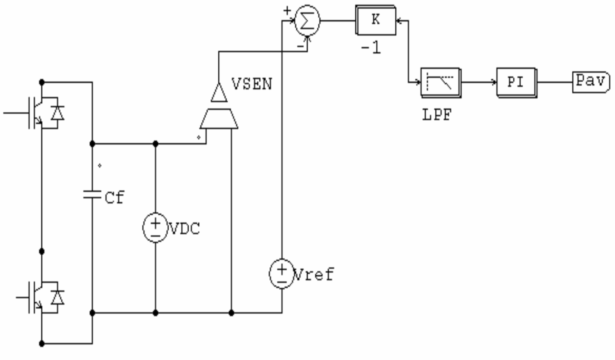

Fig. 2. The voltage loop controller.

IV. DESIGN OF CURRENT CONTROLLER

It is convenient to design the current controllers in d-q synchronous frame. The design of a P-I controller in d-q frame eliminates the steady state error since it operates on D.C quantities and the integrator has infinite gain at zero frequency [9].

In Fig.1, assuming that the line voltages at the point of common coupling are e_a,e_b and e_c whereas the output voltages of the inverter are v_a,v_b and v_c then, the voltage equations across the interface inductor are:

$$e_a - v_a = L\frac{di_a}{dt} + R\,i_a \quad ;$$

$$e_b - v_b = L\frac{di_b}{dt} + R\,i_b \quad ;$$

$$e_c - v_c = L\frac{di_c}{dt} + R\,i_c \qquad (8)$$

Where, (L) and (R) are the inductance and the internal resistance of the interface inductor respectively. These equations in the stationary a-b-c frame are transformed into the synchronous rotating d-q frame as in [9]. The coupled voltage equations are:

$$\frac{di_d}{dt} = \frac{e_d}{L} - \frac{R}{L}\,i_d + \omega\,i_q - \frac{v_d}{L} \quad ;$$

$$\frac{di_q}{dt} = \frac{e_q}{L} - \frac{R}{L}\,i_q - \omega\,i_d - \frac{v_q}{L} \qquad (9)$$

A method for de-coupling these equations is described in [10]. Two control parameters h_d and h_q are introduced. The cross coupling terms are grouped into h_d and h_q as follows:

$$h_d = e_d - v_d + \omega L\,i_q \qquad (10)$$

$$h_q = e_q - v_q - \omega L\,i_d \qquad (11)$$

Substituting h_d and h_q into (9), the simplified de-coupled state equations are:

$$L\frac{di_d}{dt} = h_d - R\,i_d \qquad (12)$$

$$L\frac{di_q}{dt} = h_q - R\,i_q \qquad (13)$$

Taking Laplace transform for both sides of (12) and (13) and rearranging, the transfer functions that relate the output parameters (i_d and i_q) to the new input parameters (h_d and h_q) can be obtained.

The components of reference reactive current in the d-q synchronous rotating frame are obtained by transforming ($i_{\alpha q}$ and $i_{\beta q}$) from the α-β frame into the d-q frame. Assuming that α-axis coincides with the d-axis, then the components of the reference reactive current i_d^* and i_q^* in the d-q frame are:

$$\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \qquad (14)$$

Where (ω) is the supply frequency. The complete closed loop current controller is shown in Fig.3.

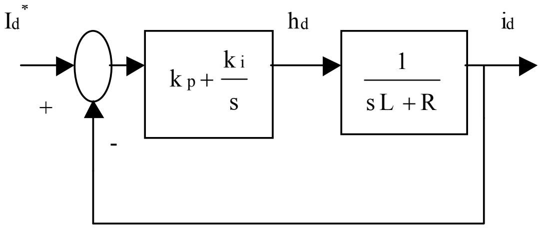

Fig. 3 The closed loop current controller.

It should be noted here that the closed loop current controller of i_q is identical to that of i_d. The design procedure of the P-I controller for a similar second order system is discussed in more details in [10]. Accordingly, the parameters of the P-I controller are found to be:

$$k_p = 2\xi\omega_n L - R$$

$$k_i = L\,\omega_n^2$$

A control criteria to select the proper values of the damping ratio (ξ), the natural frequency (ω_n) and the cutoff frequency of the interface filter, which filters out the unwanted higher harmonics of the inverter current and for simplicity is not shown in Fig.1, is also discussed in the same reference.

V. DESIGN OF THE VOLTAGE CONTROLLER

The state equation describes the current balance in the capacitor circuit is:

$$\frac{dV_{dc}}{dt} = \frac{1}{C_f}\left(S_a i_a + S_b i_b + S_c i_c \right) \qquad (15)$$

Where S_a , S_b and S_c are the switching functions of the inverter switches. For a PWM controlled inverter, these switching functions are non-linear in their nature. The output voltages of the inverter v_a, v_b and v_c can be expressed in terms of these switching functions as follows:

$$v_a = S_a V_{dc} \quad ;$$

$$v_b = S_b V_{dc} \quad ;$$

$$v_c = S_c V_{dc} \qquad (16)$$

Taking only the fundamental components of these switching functions into consideration, S_a, S_b and S_c can be written in a-b-c reference frame as [10]:

$$S_a = \frac{M}{\sqrt{3}}\cos(\omega t + \delta\,);$$

$$S_b = \frac{M}{\sqrt{3}}\cos(\omega t + \delta + \frac{2\pi}{3});$$

$$S_c = \frac{M}{\sqrt{3}} \cos(\omega t + \delta - \frac{2\pi}{3}) \tag{17}$$

Where (M) is the modulation index and (δ) is the power angle. The transformation of the equations set (17) into d-q synchronous rotating frame gives:

$$S_d = \frac{M}{\sqrt{2}} \cos(\delta);$$

$$S_q = \frac{M}{\sqrt{2}} \sin(\delta) \tag{18}$$

Applying the same transformation to the equations set of (16) gives:

$$v_d = S_d V_{dc};$$

$$v_q = S_q V_{dc} \tag{19}$$

Substituting (v_d) and (v_q) into (10) and (11), then (15) can be rewritten in terms of the control parameters (h_d) and (h_q) as follows:

$$\frac{dV_{dc}}{dt} = \frac{e_d - h_d}{C_f V_{dc}} i_d + \frac{e_q - h_q}{C_f V_{dc}} i_q \tag{20}$$

However, for more clarity, (20) can be written in terms of the cross-coupled parameters as:

$$\frac{dV_{dc}}{dt} = \frac{S_d V_{dc} - \omega L i_q}{C_f V_{dc}} i_d + \frac{S_q V_{dc} + \omega L i_d}{C_f V_{dc}} i_q \tag{21}$$

As the dynamics of the current controller is much faster than the dynamics of the voltage controller and the inductance of the interface inductor (L) is normally << 1, then, (21) can be simplified to:

$$\frac{dV_{dc}}{dt} = \frac{1}{C_f} (S_d i_d + S_q i_q) \tag{22}$$

Applying linearization to (22), the linearized- voltage state equation becomes:

$$C_f \frac{dV_{dc}}{dt} = \bar{S}_d \Delta i_d + \bar{S}_q \Delta i_q + \bar{i}_d \Delta S_d + \bar{i}_q \Delta S_q \tag{23}$$

Neglecting the dependency of i_d and i_q on the input variables S_d and S_q and taking into consideration that the voltage controller must act on the direct component of the current i.e. i_d hence, (23) is simplified to:

$$\frac{dV_{dc}}{dt} = \frac{\bar{S}_d}{C_f} \Delta i_d \tag{24}$$

The intermediate value of (S_d) which denoted ($\bar{S}_d$) in (24), is hold when the inverter output voltage and the mains voltage are equal i.e. when (e_d = v_d). In other words, this occurs only when δ= 0. Substituting for both of (δ) and the modulation index (M) by its definition in Eq.(18), then ($\bar{S}_d$) can be expressed as:

$$\bar{S}_d = \sqrt{\frac{3}{2}} \frac{V_l}{V_{dc}} \tag{25}$$

Where, (V_l) is the line r.m.s value of the inverter output voltage [11].

The closed loop voltage controller is shown in Fig.4.

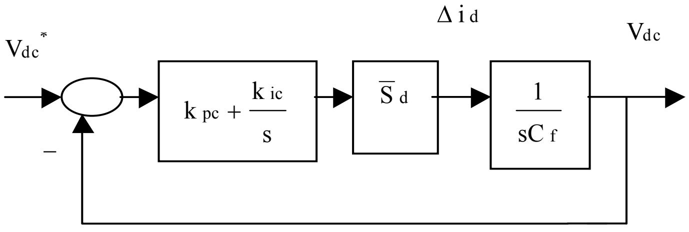

Fig. 4. The closed loop voltage controller.

The overall transfer function of this controller can be written as:

$$G_c(s) = \frac{1}{C_f} \frac{k_{pc} \bar{S}_d (s + \frac{k_{ic}}{k_{pc}})}{s^2 + \frac{k_{pc} \bar{S}_d}{C_f} s + \frac{k_{ic} \bar{S}_d}{C_f}} \tag{26}$$

Comparing the transfer function of (26) to the standard well-known transfer function of the second order system, the parameters of the P-I controller of the voltage loop can be obtained as follows:

$$k_{pc} = \frac{2 C_f \xi_c \omega_{nc}}{\bar{S}_d};$$

$$k_{ic} = \frac{C_f \omega_{nc}^2}{\bar{S}_d} \tag{27}$$

As the dynamics of voltage controller is supposed to be much slower than that of the current controller, the value of (C_f) is chosen to be 1000µF. The voltage of the D.C buss is set to be 600V. The natural frequency (f_{nc}) should be much less than 50Hz. It is selected to be (10Hz) in this paper. The low pass filter in the voltage loop controller, shown in Fig.2, is tuned to have a cutoff frequency of (70Hz). Finally, the value of the damping ratio (ξ_c) is selected to be $\frac{1}{\sqrt{2}}$ to ensures a good margin of stability and minimum percentage overshoot.

VI. SIMULATION RESULTS

The system was fully simulated using PSIM6. PSIM6 depends upon ready-made modules to imitate the performance of real circuits with high accuracy [12]. The system includes a model for 20KVA non-linear load and power factor correction capacitor (120µF,1000V) per phase. Fig.5 shows the non-linear load current, which is the supply current when providing no compensation.

Fig.6 shows the supply current and the supply voltage for phase-A after providing compensation. It is clear that the supply current became sinusoidal, smooth and in phase with the supply voltage. The system shows excellent transient response. As expected, a current was slightly high when the power switched on but it was damped rapidly and the supply current started to follow the supply voltage within the first half-cycle.

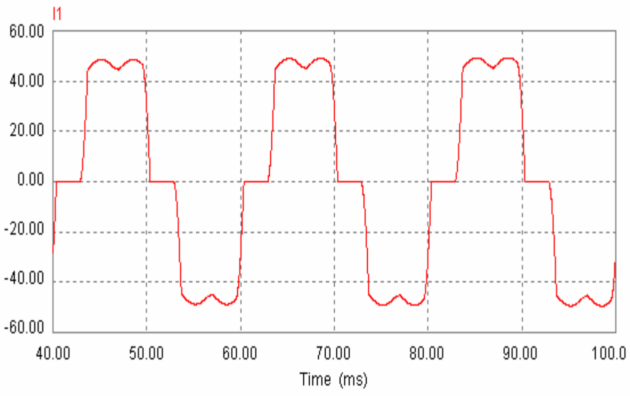

Fig. 5. The supply current without compensation.

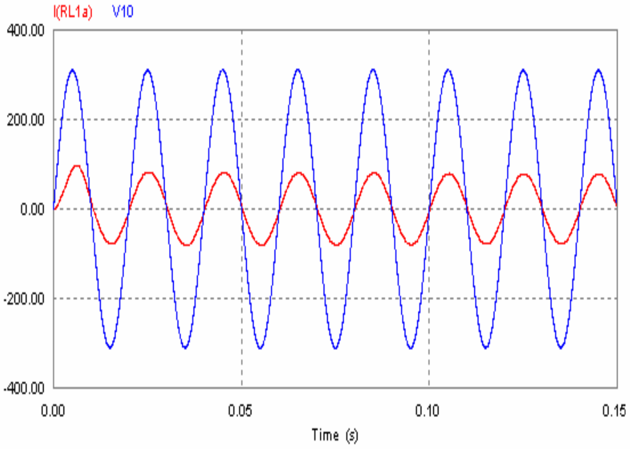

Fig.6. The supply current and voltage after compensation for phase-A.

The reactive current of the shunt active filter is shown in Fig.7. The current spikes are clear due to the effect of the P.F capacitor.

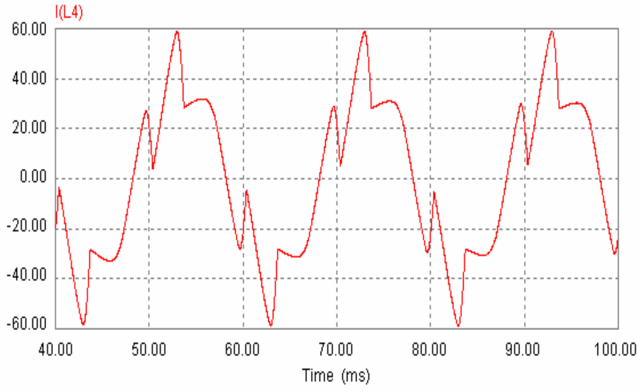

Fig. 7. The reactive current of the active filter.

The power regulated by the voltage controller (P_{av}) is shown in Fig. 8. This regulated power is a measure of the instantaneous active power exchanged between the active filter and the mains to achieve the power balance of the system.

Finally, the frequency spectrum of the supply current after compensation for phase-B, is shown in Fig.9. It is obvious that the supply current is represented by its fundamental component while all the higher dominant harmonics in the current spectrum were successfully rejected.

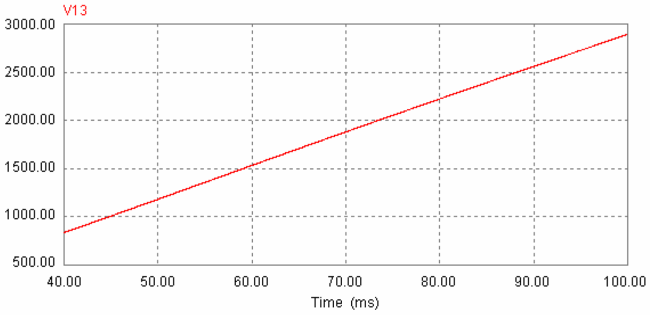

Fig. 8 The regulated average power (P_{av}).

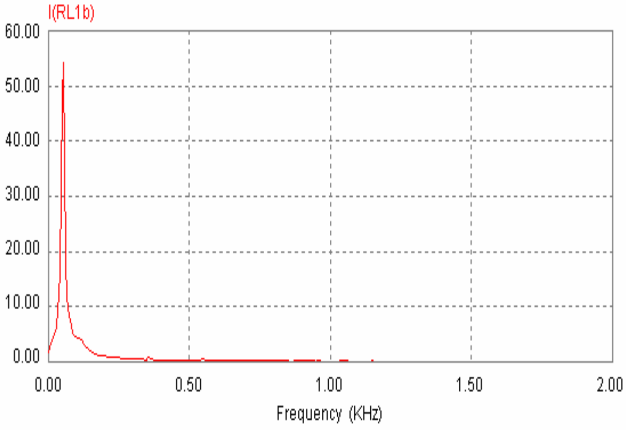

Fig.9 The frequency spectrum of the supply current after compensation for phase-B.

VII. CONCLUSIONS

Active compensation for a low voltage network comprises a non-linear industrial load and power factor correction capacitor, was investigated. The problems caused by these capacitors when they switched into the power network such as creating high voltage spikes and a low impedance path for higher dominant harmonics up-stream were overcome. The design of both the current and the voltage controllers, according to the proposed strategy, provides a clean power, a safe operation for the shunt active filter and a balanced exchange of instantaneous power between the active filter and the mains. The strategy also fits well the controlled- drives as they are mainly classified as harmonic current producing loads. Moreover, activating the policy of load identification, according to the harmonic type, can lead to an excellent compensation and solve what is called the “time- racing problem” plus the other well-known problems arise when providing on-line compensation using power active filters. Finally, the cost of applying such compensation strategy in industry can not be comparable either to the price of a production line or to the penalties that would be paid to authority on the long run.

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