A New anticipatory speed-controller for IC engines based on torque sensing loop

Dr.Abdul baki Khalaf Ali
Mechanical Engineering Department
College of Engineering / University of Basrah
Basrah, Iraq
westofbas@yahoo.com

Imad abdul-kadhem kheioon
Mechanical Engineering Department
College of Engineering / University of Basrah
Basrah, Iraq
phdimad@yahoo.com

Mushtaq Kadhim Ali
Mechanical Engineering Department
College of Engineering / University of Basrah
Basrah, Iraq
mushtaqkadhim@yahoo.com

Abstract—**Some engineering applications requires constant engine speed such as power generators, production lines ..etc. The current paper focuses on adding a new closed loop based on engine torque. Load cells can be used to measure the torque of load applied , the electrical signal is properly handled to manipulate a special fuel actuator to compensate for the reduction in engine speed. The speed loop still acts as the most outer closed loop. This method leads to rapid speed compensation and lead control action.**

KEYWORDS :Speed control , IC engine , Torque ,Compensation, Generator set

INTRODUCTION

Designing a robust speed controller is an important mission especially for application that requires constant speed. The engine-Generator set (GS) ,for example, requires constant engine speed to ensure constant frequency for the power generated. When a sudden load is applied to the generator, the speed show a sudden drop for a short period of time till the speed controller recover the rated engine speed. This drop in speed lasts for a short period of time. In simple application this is not a problem, but in some application this short time may case a real problem.

The closed loop controller for speed control of IC engine is ,generally, as shown in Fig.1.[1]

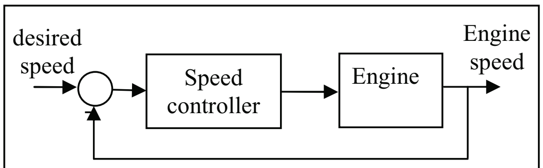
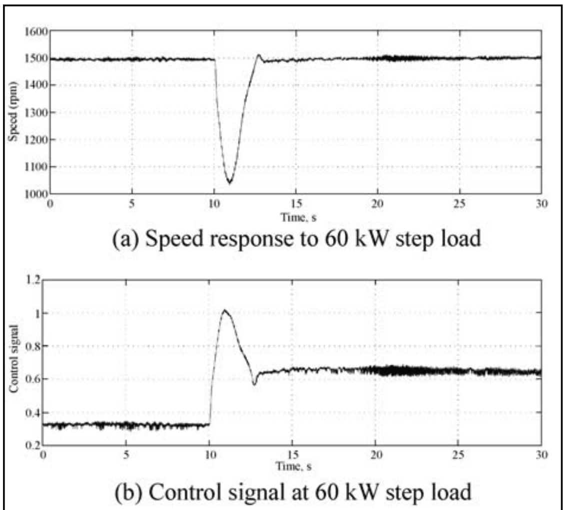


Fig. 1

Conventionally , three-term, proportional-integral-derivative (PID) feed back controller are widely used as speed controller [2] because of their low computational requirements and simplicity of tuning . However ,their main drawbacks are poor performance compared with that of modern control theory implemented on the same hardware and that optimal performance is not necessarily guaranteed under all operating conditions [3] .

When sudden load is applied to the generator set (step load) ,the speed begins to retard , the controller starts to take action when considerable change in speed occurs . This can cause the engine speed to show a noticeable. Fig.2 [4] shows engine speed and controller action when a load of 60kW (93%) of engine capacity is applied. It is clear that the speed drops for a noticeable period of time .



(a) Speed response to 60 kW step load

(b) Control signal at 60 kW step load

Fig.2 [4]

Figure.3 [4] shows the engine responses due to different types of controller these are the PI, commercial and a new developed by[4] ,which called 2nd-sliding. It is important to notice that there still a significant period of time where engine speed below the rated one .

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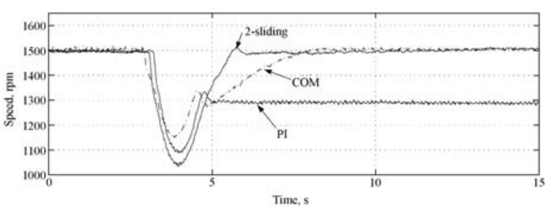


Fig.3 [4]

The new developed controller (TFCC)

The new developed controller ,namely, Torque –fuel compensation controller (TFCC) focuses on the major disadvantage of the conventional controllers . It approves the anticipatory and reduces the emissions and fuel loss. Its action start immediately with the leading edge of external load . The torque sensors, which are simple appropriate load cells , account the amount of torque applied . An electrical signal is released and directed to the signal conditioning unit (SCU).

Fig.4 shows two control loops: The conventional , speed loop and the new, torque loop. The speed loop is similar to that shown in fig.1 it acts for long term phase. In most commercial controllers, it is proportional , sometimes integral action is added to eliminate steady state errors. The other loop, the torque loop, acts for transient and short term actions.

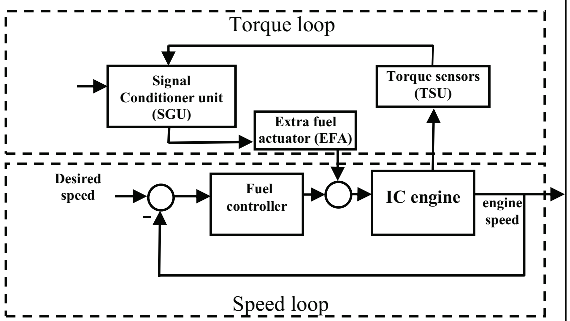


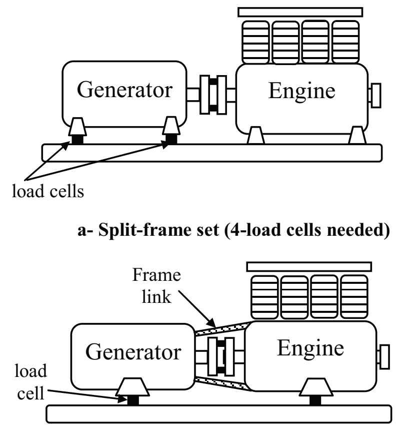
Fig.4 Control loops

The torque loop consists of three major units: The torque sensing unit, the signal conditioning unit (SCU) and the Extra fuel actuator unit (EFA)

1- The torque sensing unit (TSU) : This unit consist simply of the load cells attached either to the load (generator) brackets or to the flexible support of the engine-generator set. The position is indicated according to the method of coupling used in the generator set. For the split-frame set shown in fig.5-a , four load cells are needed under the four feet of the generator. For the linked frame set the load cells are attached to the four flexible supports as shown n fig.5.b

Split-frame set analysis

In this case ,the load cells can be calibrated to express the total generator load acts on the engine.



a- Split-frame set (4-load cells needed)

b- Linked-frame set (4-load cells needed)

Fig.5 Load cell installation

When a step electrical load is applied to the generator , the load seems to add braking force on the rotor. The reaction appears as a rotational kick $\mathbf{T_L}$ on the generator frame (stator).This will cause the generator to try to spin or rotate about its center. Fig.7 shows force balance. In split frame generator set, both engine and generator are set on hard and accurate supports to prevent relative motion which may harm the coupling. The expected formula for the load torque can be expressed as follows:

$$\mathbf{T_L = a * [Force\ (RH) - Force\ (LH)]} \quad \textbf{(1)}$$

$$T_L = a * C1 * [reading\ (RH) - reading\ (LH)] \quad \textbf{(2)}$$

Where C1 is the load cell constant(N/mV)
Or with other words, If we let $\mathbf{F_{LC}}$ the relative load cell force between right and left hand cells then,

$$\mathbf{T_L = aC_1F_{LC}} \quad \textbf{(3)}$$

,which means that the load cell readings are proportional to the added load torque.

Linked frame set analysis

For the case of linked frame set (fig.5-b) , there is some difficulties. It is not possible to measure the external

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load by the load cells. The load is regarded as internal between the

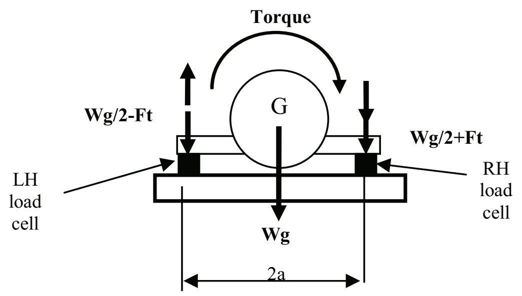

Fig.6 Load cell forces

engine and the generator and the two machine are linked hardly by the linking frame. Instead of measuring the external load, The load cell can pick the change in load. When a step electrical load is applied to the generator , the load seems to add braking force on the rotor. The reaction appears as a kick on the generator frame (stator). Fig.7 shows the force balance in the case of linked frame set.

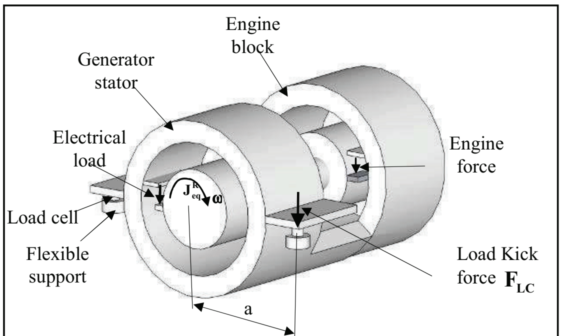

Fig.7 Schematic Load balance for linked frame generator set

To estimate the magnitude of the kicking force ,fig.8 shows a simple proportional controller , T_L represents the electrical load, T_E is engine developed torque, ω_r is change in reference speed (which is usually zero), J^R_{eq} is the equivalent second moment of the rotational parts (generator rotor and crank assembly) , f :is the friction term and ω is change in engine speed. If we start with ω =0, then it is possible to show :

$$T_e = \frac{K_p}{J^R_{eq}s + (K_p + f)} T_L \quad (4)$$

Eq(4) represent engine response to the load torque, it is in opposite direction and hence the net torque which acts on the rotor (T_{Net}) is :

$$T_{Net} = T_L - T_E \quad (5)$$

$$T_{Net} = T_L \left[1 - \frac{K_p}{J^R_{eq}s + (K_p + f)} \right] \quad (6)$$

$$T_{Net} = T_L \left[\frac{J^R_{eq}s + f}{J^R_{eq}s + (K_p + f)} \right] \quad (7)$$

It is possible now to write force balance to estimate the kicking force measured by the load cell. The kicking force cause the whole GS to spin or rotate about its center for small angle and then return to equilibrium. Let J^{RS}_{eq} be the total second moment for rotational and stationary members including (generator rotor, crank assembly, generator stator and total engine block).

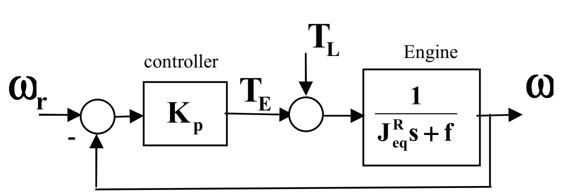

Fig. 8 simple proportional speed controller

Let Ω be the twist angle of the whole GS.

$$T_{Net} = J^{RS}_{eq}s^2\Omega + aF_{LC} \quad (8)$$

Referring to fig.8, The GS is mounted on flexible members. Let K_m be the stiffness of flexible member.

$$\Omega aK_m = F_{LC} \quad (9)$$

Substitution of eq(9) in eq(10) gives :

$$F_{LC} = \frac{1}{(\frac{J^{RS}}{aK_m}s^2 + a)} T_{Net} \quad (10)$$

$$F_{LC} = \frac{1}{(\frac{J^{RS}}{aK_m}s^2 + a)} \left[\frac{J^R_{eq}s + f}{J^R_{eq}s + (K_p + f)} \right] T_L \quad (11)$$

Now if consider that the friction force (f) is small relative to inertia and external loads and can be set to zero, The laplace transform of T_L is T_L / s then :

$$F_{LC} = \frac{T_L}{(\frac{J^{RS}}{aK_m}s^2 + a)} \frac{J^R_{eq}}{(J^R_{eq}s + K_p)} \quad (12)$$

$$F_{LC} = \frac{\frac{aK_m}{J^{RS}}}{(s^2 + \frac{a^2 K_m}{J^{RS}})} \frac{T_L}{\left(s + \frac{K_p}{J^R_{eq}}\right)} \quad (13)$$

$\mathbf{F_{LC}(t)}$ is obtained by inverse laplace transform of eq(13):

$$F_{LC}(t) = T_L [A_1 \sin \Omega_1 t + A_2 e^{-\frac{t}{\tau}}] \quad (14)$$

Where $\tau = \frac{J^R_{eq}}{K_p}$ and $\Omega_1 = \sqrt{\frac{a^2 K_m}{J^{RS}}}$, A1 and A2 are constants.

Eq(14) gives the relation between load cell reading and increase in torque load. It is important to notice that the load cell loads, F_{LC} consist of a small sinusoidal component and an exponential-time vanishing component. Practical observation shows that the generator set returns to its equilibrium position after complete speed compensation. The oscillatory term is of small importance and not dominant since Ω_1 is of small value and the kick time is short. The simplified form for the linked frame set is

$$F_{LC}(t) = T_L A_2 e^{-\frac{t}{\tau}} \quad (15)$$

Eq(15) shows that the load cell reading appears as a pulse at the time of applying the additional torque and it vanished with time .This is different from eq(3) for split frame set, where the load cells show a step reading and of amount proportional to the extra torque and stay constant with time. The load cell readings of eqs(3) and (15) are directed to the second unit (SCU).

The Signal conditioning Unit (SCU).

The load cell measure the amount of load and convert loads to electrical signals (mV/V) . These signals are of small power and cant drive control actuator. This unit can be used to calibrate load cells, amplify their reading and account the appropriate gain to drive the extra fuel actuator. Practical tuning can be carried to choose the correct value of K_{PT} .

The Extra fuel Actuator unit (EFA):

This units needs to be built according to many practical considerations. For example the type of IC engine (SI or CI) need to be controlled, the type and size of fuel pump or fuel injectors , presence or absence of electrical actuators in the structure of the fuel pump…. etc.

EFA in SI engines:

If our problem was to control the speed of (SI) engine , then the loop of torque compensation is easy to implemented. The EFA will be an additional fuel injector mounted in the intake manifold. This injector receives the opening signal from the (SCU). An amount of fuel proportional to the signal of the (SCU) will be injected and immediately at the moment of application of external load.Fig.10 shows two proposed method for EFA in SI engine. The first is to add an individual injector as apart of the torque loop(fig.9-a). The second method is to interact with the existing one (Fig.9-b) . In both methods the EFA inject fuel for a time (ms) commanded by the unit (SCU).

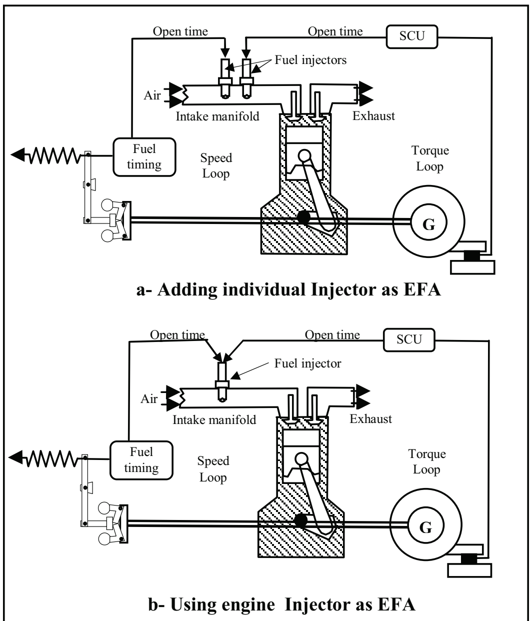

Fig. 9 Proposal for EFA in SI engines.

EFA in CI engines:

If the problem was to control the speed of (CI) engine , which is the case in most medium and large size GS applications, then it is important to study the structure of the fuel system as a whole.

Some fuel pumps have electrical actuator to provide the integral action to eliminate steady state errors. Our work can be interacted with this actuator and it can be used as (EFA). In other simple fuel systems The EFA can be implemented with an electrical actuator. The actuator is to be mounted to pull the speed rack against the centrifugal force and to allow for extra amount of fuel to be injected by the fuel pump(Fig.10)

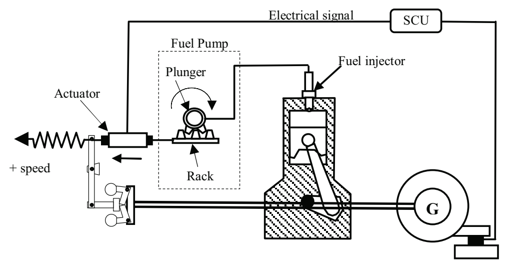

Fig. 10 Proposal for EFA in CI engines.

Results and discussions

All the following results are built according to the mathematical modeling of both speed and torque loops discussed above and no practical experiments are carried.
Two cases considered for discussion. One for the split frame set and the other for linked frame set. The discussion based on the early response of the torque loop as a measure of that of the speed loop. .

A- For split frame GS

Referring to eq(4) which express the engine response T_E as a function of added load T_L in laplace domain and as a part of speed control loop, For small frictional term (f) , the time domain response is :

Error! Objects cannot be created from editing field codes. (16)

This is a first order system with $\tau = \frac{J_{eq}^{R}}{K_p}$, the load cell reading according to eq(3) can be rewritten as :

$$F_{LC} = \frac{T_L}{aC_1} \qquad (17)$$

The F_{LC} goes as electrical signal to (SCU) which produces proportional action to the EFA and the proportional torque **Error! Objects cannot be created from editing field codes.**,which is the developed torque due to torque loop :

$T_{ET} = K_{PT} T_L$ where K_{PT} is the gain of the torque loop.

Fig.11 shows a sample response for an IC engine subjected to a step load T_L at a time (t=1sec), The speed loop responses (T_{E1} , T_{E2}) are corresponding to loop gain (K_{P1} and K_{P2}) where (K_{P2} greater than K_{P1}). In both cases the system need a time equal to τ to reach about 63.2% of the torque load T_L .

On the other hand , the torque loop can produce a torque (T_{ET1} and T_{ET2}) corresponding to loop gain (K_{PT1} and K_{PT2}) where (K_{PT2} greater than K_{PT1}). It is clear that the control action for this loop start immediately at the moment of applying load. Changing the value of gain loop can result in change in magnitude of action not time of action. This is the most important advantage of the torque loop added in this paper over the conventional speed loop .

B- For Linked frame GS

Figure 12 shows the results for linked frame set . When an external step load is applied at (t=1 sec), the engine starts to produce an equivalent torque according to the speed controller. The results for increase in external load (T_L) , engine response due to speed controller (T_E), the difference between load and engine torque (T_{NET}) and the control action due to torque loop (T_{ET}). The results here show advantage for the torque loop against the speed loop. It is the lead action. The net torque cause a transient kick on the supports of the GS . When the engine begins to resist the load

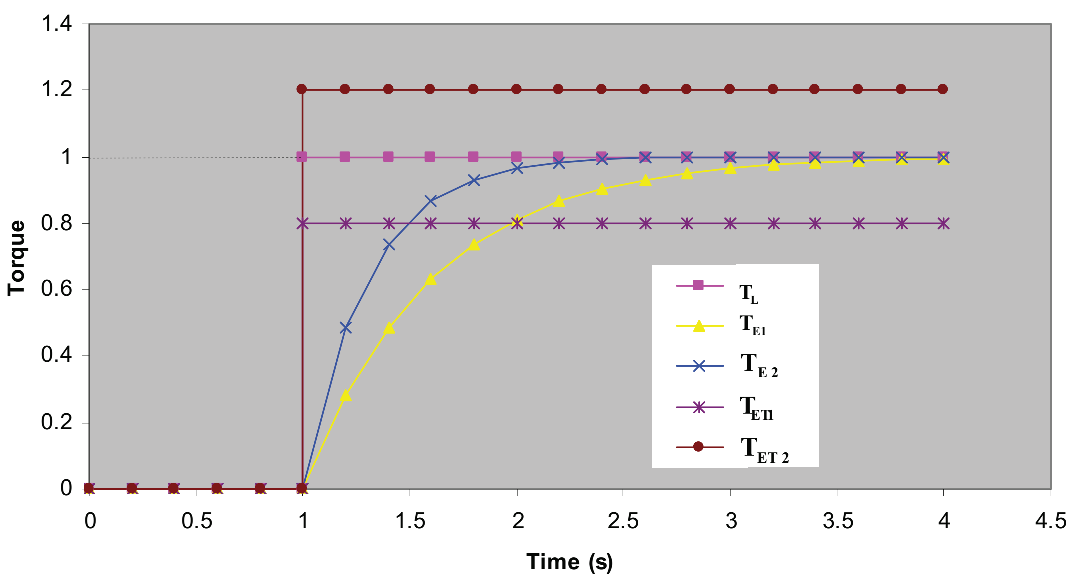

Fig. 11 Control action for speed and control loops (split frame set)

torque the value of the net torque return to zero. The torque loop action express behavior close to the value of the net

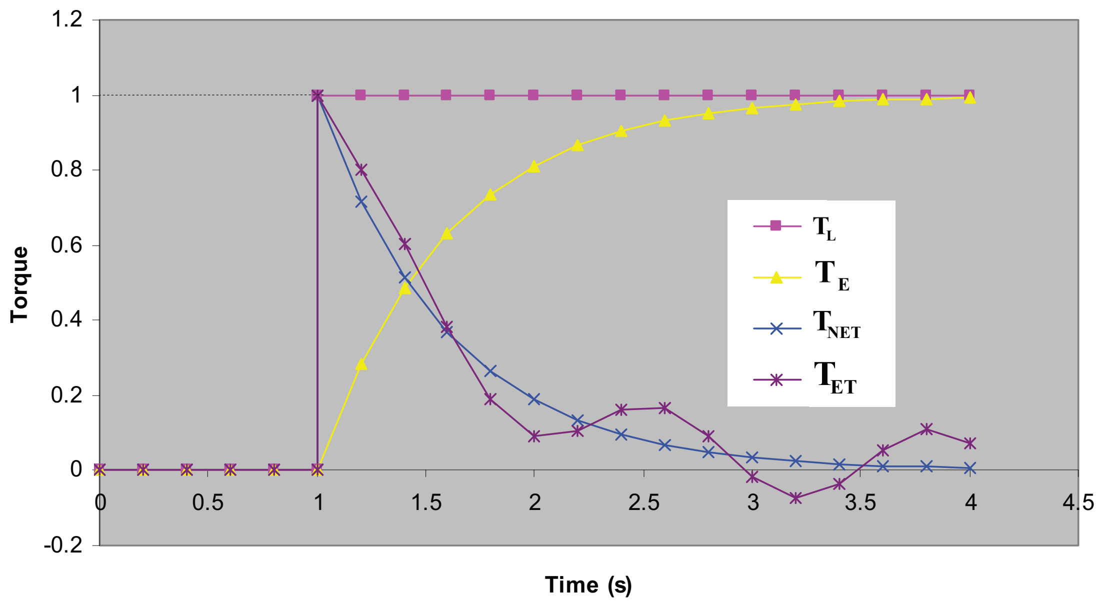

Fig. 12 Control action for speed and control loops (Linked frame set)

torque. The value of this action has the advantage of big value at early time of applying load which gave enough time for engine to recover its rated speed.

CONCLUSIONS

Adding torque loop to the speed controller of IC engines can improve transient response of speed controller and reduces the raise time. This lead action results from the early control action that released simultaneous to the applied load. Changing the gain of the torque loop can change the magnitude of the action but not the temporal parameters of response. This is a simple method and can save the cost of building complicated torque model [5], or Neural network controller [6] to precisely control engine speed.

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