THE DESIGN AND DEVELOPMENT OF THE XK8 CHARGING SYSTEM

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1. INTRODUCTION

An automobile charging system appears at first to be a very simple system. It basically consists of a rechargeable storage battery that is used to start the vehicle and a generator which is used to ensure that the battery is recharged. However, this simple system can be difficult to implement due to the following, often conflicting, requirements and limitations:-

• In addition to charging the battery, the generator must also be able to supply the electrical power requirements of the vehicle. These power requirements vary dramatically with climatic conditions and vehicle specification, (heated screens, air conditioning systems, electric cooling fans etc), and can be as high as 2 - 3KW. With improving engine efficiency, average engine speeds are tending to fall so as to enhance fuel consumption and vehicle refinement. Also, due to increasingly tightly packaged and sealed engine bays, the generator can experience high temperatures, even in Winter conditions. Unfortunately, the output power of the generator reduces with increasing temperature and reducing engine speed so the modern automobile is an increasingly hostile environment for the generator.

• The battery must contain enough power to drive the starter motor at a high enough speed and for a suitable time to start the engine under any climatic conditions. Unfortunately, the chemical activity of a battery reduces with temperature such that, at very low temperatures, its output power capability can be reduced by up to 50%. However, with more advanced engine management and fuel systems, engines are now able to be started in a shorter time and with lower crank speeds than was the case for carburettor fed engines. This improvement, though, is more than offset by increasing vehicle electrical complexity, which leads to greater demand for the battery to support electrical systems while the car is switched off, (eg alarms, engine management systems, navigation systems etc). While the demanded current is usually only in the order of mA, it can have a significant effect upon the state of charge, (and therefore output power capability), of the battery if the vehicle is left for a long time. Consequently, the battery size is now driven more by such 'Key Off Loads' than by the vehicle starting requirements.

• The vehicle cost, fuel consumption, performance and refinement are affected, to different degrees, by the size of the battery and the generator so, whilst the charging system would ideally consist of a battery powerful to satisfy the above requirements and a generator big enough to ensure it is never discharged, such components would be large and heavy and not used to their full capacity for the majority of the vehicles life. The resultant charging system would therefore reduce vehicle efficiency and increase its lifetime cost to the customer. In order to minimise their impact on the vehicle, it is necessary to choose the smallest and most efficient components possible that will still ensure that the customers, wherever they live, will always be able to start the vehicle whilst incurring the lowest cost penalty possible.

This paper will describe the process by which Jaguar provides the optimal charging system for its vehicles, and concentrate upon the simulation tools used to enhance this process and allow the components specification to be fixed as early as possible in the design process.

2. FACTORS AFFECTING COMPONENT CHOICE

Battery

1. Power required to start the engine. This is defined by the starter motor used, the effectiveness of the engine management system and the friction characteristics of the engine.

2. Power required to support vehicle systems when left standing. This is determined by the total current draw of the vehicle Key Off Loads and the required time for which the vehicle may be left and still start.

3. Battery Dynamic Performance. This is the ability of the battery to operate satisfactorily throughout the vehicle life and covers such factors as energy throughput, deep discharge recovery, charge acceptance and operational environment. It is not a factor that can be defined without question and forms a central area of investigation during the design and development of a charging system.

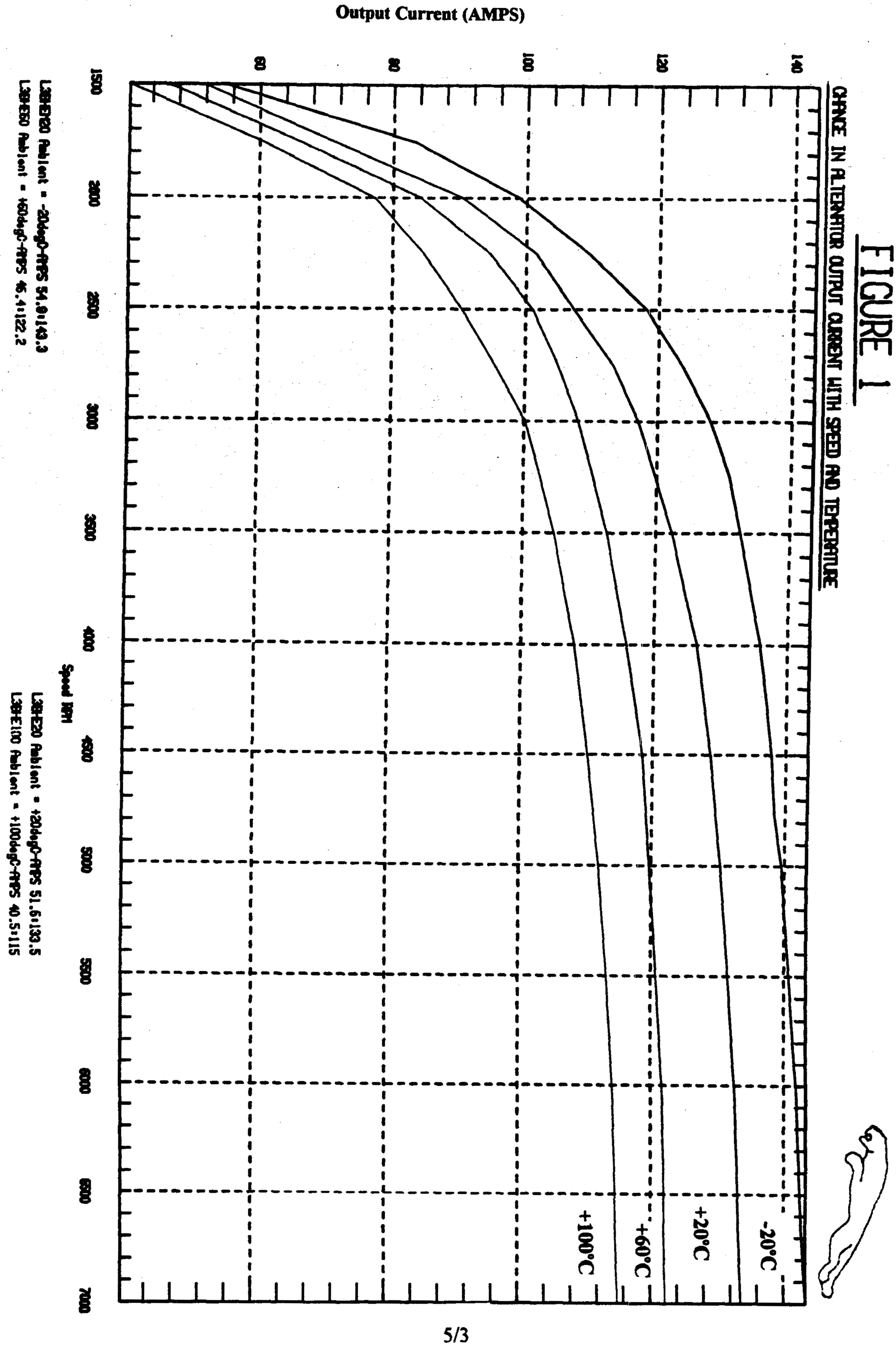
Generator

For present car electrical systems the generator must provide a nominal 12V DC power output. Therefore, it may either generate DC power directly, (a dynamo), or generate AC power which is then rectified to DC, (an alternator). The alternator uses brushes moving around smooth slip rings to provide power to its rotor, so it's brushes do not wear as quickly as those of a dynamo, which move around a commutator. As a commutator comprises a number of separate segments, the brushes of a dynamo suffer higher electrical stress due to current fluctuations and sparking as they move between segments and mechanical wear due to passing over the segment edges. Also, modern vehicles tend to have engines with high maximum and transient speeds in addition to carrying increasing electrical content. This leads to higher generator speeds being required in order to be able to supply the necessary electrical power. The dynamo cannot economically attain the speeds required by modern vehicles due to commutator and rotor construction limitations. However, as the alternator is basically an AC generator it has no commutator and the rotor construction used for such machines is more robust and capable of much higher sustained and transient speeds than a dynamo. The alternator is also able to provide a higher power density thus allowing a smaller and lighter package to be obtained than for a dynamo with a similar power output.

Therefore, as the alternator is better suited to automotive applications and is now almost universally used, only the use of an alternator coupled to the engine by a belt drive, giving a driven speed proportional to engine speed, will be considered here.

1. Engine Speed range. The alternator must supply electrical power throughout the engine speed range. Typical alternator output characteristic curves are shown in Figure 1 and demonstrate that the output varies significantly at the lower third of its speed range but will hardly increase at all up until a typical maximum continuous speed of 18,000 RPM. Therefore, the alternator must have a drive ratio that ensures its speed does not fall too low whilst also ensuring that it will not be driven to destruction.

2. Alternator Drive. This determines the maximum allowable drive ratio for the alternator and depends upon the type of drive belt, the number of other components using the same belt, power absorption of all the driven components, engine transient speed characteristics, environmental conditions and the required belt life.


Output Current (AMPS)
FIGURE 1
CHANGE IN ALTERNATOR OUTPUT CURRENT WITH SPEED AND TEMPERATURE
140
120
100
80
60
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
Speed RPM
-20°C
+20°C
+60°C
+100°C
L38HE20 Ambient = -20degC-AMPS 54.9:143.3
L38HE60 Ambient = +60degC-AMPS 46.4:122.2
L38HE20 Ambient = +20degC-AMPS 51.6:133.5
L38HE100 Ambient = +100degC-AMPS 40.5:115

3. Vehicle Electrical System. This encompasses the electrical sub-systems fitted to the vehicle and their power consumption requirements, the nominal system voltage, the type of wiring used for the main power feeds, and the type of battery used. It provides a complex set of requirements to be satisfied and provides one of the main challenges for charging system engineers.

4. Environment. The position on the engine where the alternator is sited, the layout of the engine bay and even the styling of the car can have significant effect upon alternator performance and durability.

5. Vehicle Effects. The alternator creates noise which increases with speed as well as drawing increased power with reduced efficiency. Therefore, it is necessary to have the lowest possible alternator speed whilst still providing the required electrical power to support the vehicle.

All the above requirements must be considered when designing a charging system, in addition to keeping the weight as low as possible and ensuring that the resultant system cost is justifiable.

In order to improve reliability, engine designs are often now fixed before the vehicles in which they are intended to be used are even designed. Therefore, it is necessary to make correct and optimal sizing decisions for the charging system as early as possible. The following text describes the tools and methods which Jaguar utilise to achieve this and how the system is proved out and continually modified until the vehicle project reaches production.

3. SIMULATION

Simulation is normally considered to be entirely computer based with the charging system being modelled mathematically. Unfortunately, an accurate mathematical model has yet to be created which can be applied to all types of lead-acid battery. Because of this, computer based models tend to be of limited use due to their inaccurate and rather generalised predictions which can lead to a lack of confidence in the charging system sizing decisions until actual vehicles are tested. Jaguar does use a computer model as part of the charging system sizing process but the main simulation process is performed using a test rig which uses real alternators and batteries, configured and loaded to the same conditions as a vehicle, in order to provide the necessary confidence to commit to specific components very early during a vehicle project. This section is split into two parts in order to separately discuss both areas of the simulation process.

3a. Computer Based Simulation

The charging system is relatively easy to simulate when under steady state conditions, such as a constant speed at a constant temperature with a fully charged battery. This is because when the vehicle has reached such a condition, the electrical system load will usually have also reached a steady state. Therefore, the charging system performance under such conditions is a simple mathematical operation where the maximum alternator output current is obtained from examining its output characteristics and then the total vehicle load current is subtracted from it. This form of simulation is ideally suited to computer modelling techniques.

However, the majority of a vehicles life is likely to be spent under more dynamic conditions with the temperatures, load current and vehicle speed all varying and the battery is therefore likely to experience constant energy throughput of either a charge or discharge nature. This is much more difficult to model accurately as it requires having an accurate mathematical model of the components under dynamic conditions .

The usual form of charging system simulation calculates the average vehicle load current over a particular test cycle and subtracts it from the average alternator output current. The alternator current is calculated by inputting the average engine speed for the test cycle and multiplying it by the proposed drive ratio to obtain the alternator speed. This value is then used to obtain the alternator current from its output characteristics, (which are usually provided by the alternator supplier), for a particular temperature . This process has the following benefits:-

- Different types of alternator can be quickly assessed.
- The effect of varying parameters such as engine speed, load current duty cycles or alternator drive ratio can be assessed.

Unfortunately, the process also has the following weaknesses:-

- Manufacturers alternator output characteristics never truly reflect the conditions experienced in a vehicle. This is because they are measured for constant temperature conditions. The temperatures seen on a vehicle are continually varying so the alternator output current for a vehicle under test may be significantly different from that predicted by using the suppliers performance characteristics.

• The battery performance is effectively ignored. It is usually assumed that if the end result of the simulation is positive, then the battery will be charged, which assumes that the battery will accept whatever excess current that the alternator can provide. However, in reality this depends on a number of factors which are difficult to simulate or which cannot be modelled, such as system voltage drop, battery voltage and battery charge acceptance capability. Any of these factors can lead to an ineffectual or inefficient charging system despite a promising simulation result.

The simulation program used by Jaguar adopts a different approach as, instead of averaging the data, it runs a 'pseudo real time' simulation of charging system tests. It was written entirely in house and is an event driven simulation.

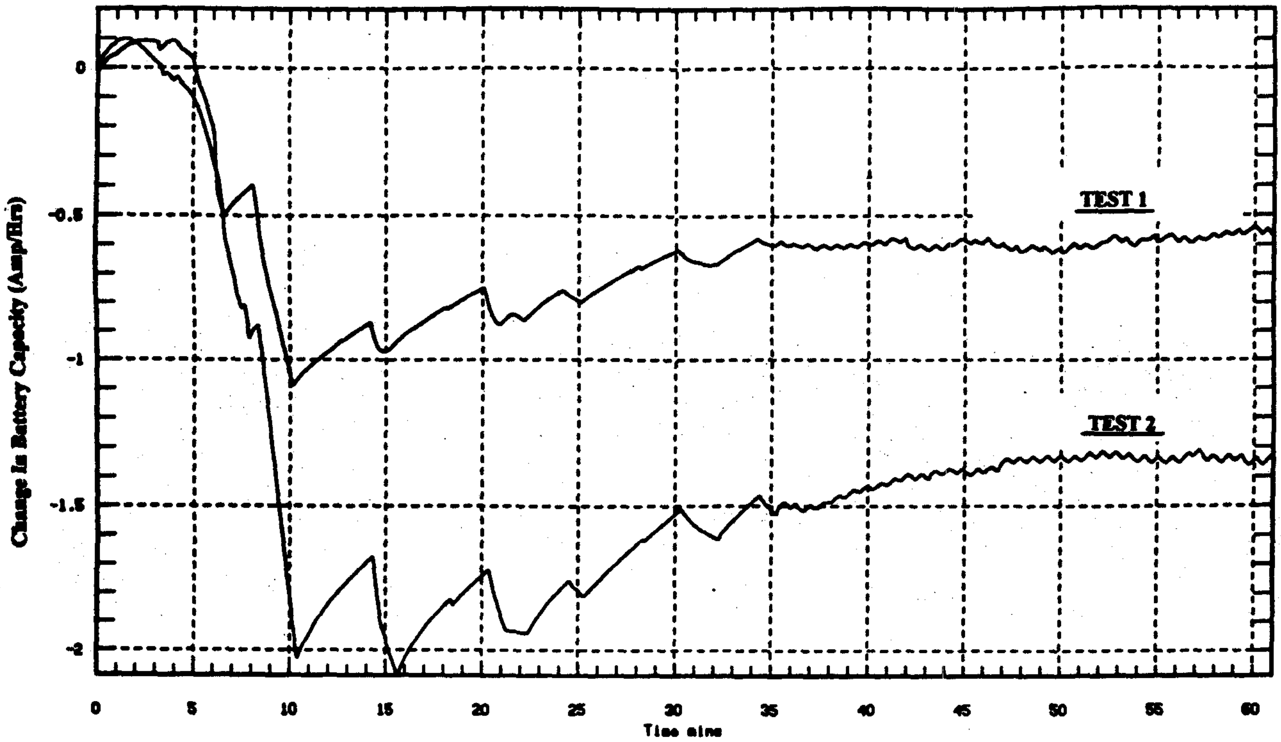
The user may program in a test cycle in the form of a time series of events. Events are identified by time and can be as close together as required but the time elapsed between events does not have to remain constant. The parameters used are assumed to remain constant between events so the number of events used for a simulated test significantly affects the accuracy of the result. At each 'event', a number of parameters, such as alternator and battery temperature, engine speed and whatever electrical consumers are operating, are set. The electrical consumers are chosen from a separate file which already contains the values of load current so, once a particular file of electrical loads has been chosen from a database, the user has only to be concerned with which consumers are switched on. Not every parameter must be set when an event is entered as, if any parameter is not set, then it is automatically assumed to have remained at the same state or value as the previous event in time. In this way, a detailed test cycle can be relatively easily programmed.

When a test simulation is performed, the user selects previously programmed test cycle, and alternator output characteristic files and then sets various factors such as alternator drive ratio, various special EMS based functions, battery size, battery state of charge and battery efficiency. The simulation then steps through every event in the test cycle in time sequence and calculates alternator, electrical load and battery current and battery state of charge, (based upon continuous integration of the battery current in conjunction with set efficiency factors).

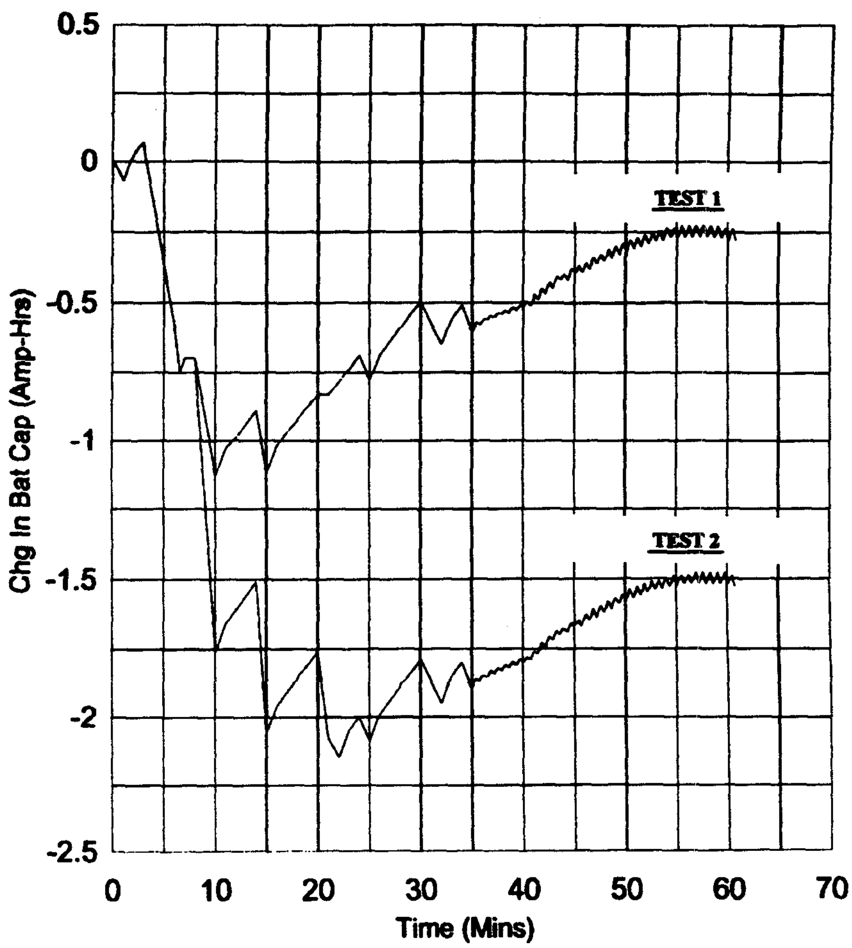
The resultant output file provides the computed and set values for each event and is stored on disk. It can be printed out to the screen or a printer in tabular form and can also be imported into a spreadsheet program to allow analysis of the test. Data from actual vehicle tests has been input into the simulation program to determine how accurate the simulation can be and a typical output from the simulation program is shown in Figure 2 against the result of the actual tests that were used as a source of input data.

FIGURE 2 - COMPUTER SIMULATION PERFORMANCE WHEN USING REAL VEHICLE TEST DATA AS INPUT DATA

VEHICLE TEST RESULTS



SIMULATION PROGRAM RESULTS



In addition to the advantages given for the averaging approach to charging system simulation, this event driven simulation program provides the following further advantage:-

- It allows a continuous trend of currents and state of charge to be assessed which helps the engineer to pin-point particular sections of the test cycle where the performance is likely to be unsatisfactory. This reduces the amount of simulations that are required to ascertain charging system performance as recursive simulations quickly allow the engineer to isolate factors that need to be examined in more detail and eliminate those of little interest. By contrast, the averaging process merely provides average values for the entire test and gives no indication to the engineer of where improvements may be made which then requires the engineer to 'guess' what to try next in order to improve system performance. Also, by using average values the engineer will only know that a result is either good or bad and will not be able to assess if the chosen components provide optimal performance, (ie assessment of alternator capacity utilisation for example). By examining the graphical trends obtained from the Jaguar program, the user can more easily identify if further improvements can be made and what combination of changes may have a significant effect.

Unfortunately, the Jaguar simulation does suffer from the following limitations:-

- The battery performance is simulated using factors obtained empirically from numerous tests. This method still suffers from accuracy limitations and can only be used as a guide to charging performance.
- The effect of system voltage cannot be assessed which means that voltage regulator settings cannot be assessed and the simulation therefore suffers further errors as, even though the electrical load current will vary with voltage, it is assumed to be constant for the simulation program.
- The alternator characteristic file uses a single output characteristic and a degradation factor of -A/°C to simulate the effect of temperature. This provides further errors as the alternator output reduction with increasing temperature is, in fact, non-linear. This could be improved by using a number of output characteristics for different temperatures but, given the above battery limitations and the fact that Jaguar has a simulation rig which uses real components, it is not considered to be worth the extra effort to include the feature.

For the XK8, (and subsequent models), this 'event driven' computer simulation program has been used to determine which alternator is worth testing and to provide the most likely optimal drive ratio and idle speed combination. It also provided an initial indication of where problems were likely to occur and which areas were likely to require more detailed investigation. This saved time and effort as testing a large number of alternators and drive ratio combinations using the test rig can be prohibitive in terms of the resource required to support the tests and the time taken to complete them.

For the XK8, a total of 15 alternators from 6 possible suppliers were assessed by using this simulation program. The results allowed the number of alternators actually tested to be reduced to 6 machines from 4 suppliers. These remaining prospective suppliers were then required to supply actual component samples for rig testing.

3b. Charging System Simulation Rig.

A schematic of the Jaguar charging system simulation rig is shown in Figure 3. It consists of two environmental chambers containing up to two alternators in one chamber and up to two batteries in the other. The components are connected with cabling that is as close to the real vehicle wiring harness as possible and electrical system load is provided by two variable load banks. The individual components can be interconnected or run as two separate systems. The alternators are driven through a geared drive by a motor controlled by an inverter drive and the batteries sit upon a tray which can be rocked to simulate vehicle motion. There is also the facility to simulate the effect of air movement around the components if required. The entire rig is controlled by a Programmable Logic Controller which is sited in the main control cabinet along with digital displays for the measured component parameters. The controller allows different test cycles, stored on floppy disk, to be loaded when required and the measured test data is stored on a PC via a serial communication link.

When the remaining prospective suppliers for the XK8 provided samples of the requested alternators, they were all subjected to the same batch of tests as follows:-

a. Output current characteristic measurement throughout the entire temperature range.
b. Voltage regulator performance throughout the entire temperature and load current range.
c. Simulated vehicle test cycles as part of a charging system.

These tests allowed the manufacturers claims for the alternators to be checked throughout their entire operational range as well as determining their performance when operating in a dynamic test cycle with a real battery. The use of the test rig also allayed supplier concerns about any anomalies in comparing data from different manufacturers as all the components were tested by Jaguar engineers under identical conditions.

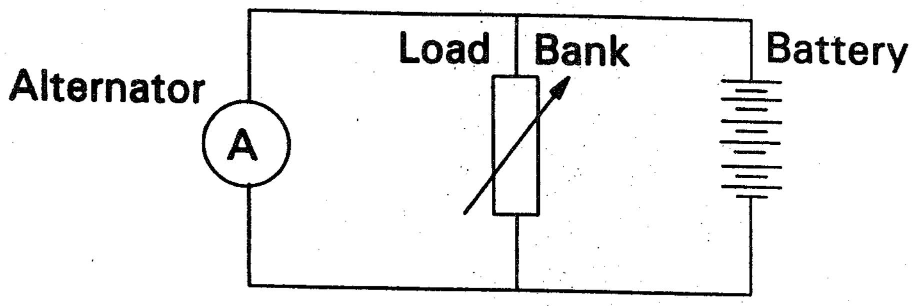
The result of this initial batch of tests was as follows:-

- The optimal alternator and drive ratio combination was chosen before a prototype vehicle was built.
- Initial data was obtained about the likely performance of the XK8 charging system and, based upon this data, a further rig test program was initiated to further investigate areas that could possibly be improved.
- All XK8 vehicle tests, when performed much later in the project, used the same alternator and drive ratio. This meant that the tests were used for optimising the vehicle charging system and not attempting to choose the correct alternator and drive ratio.

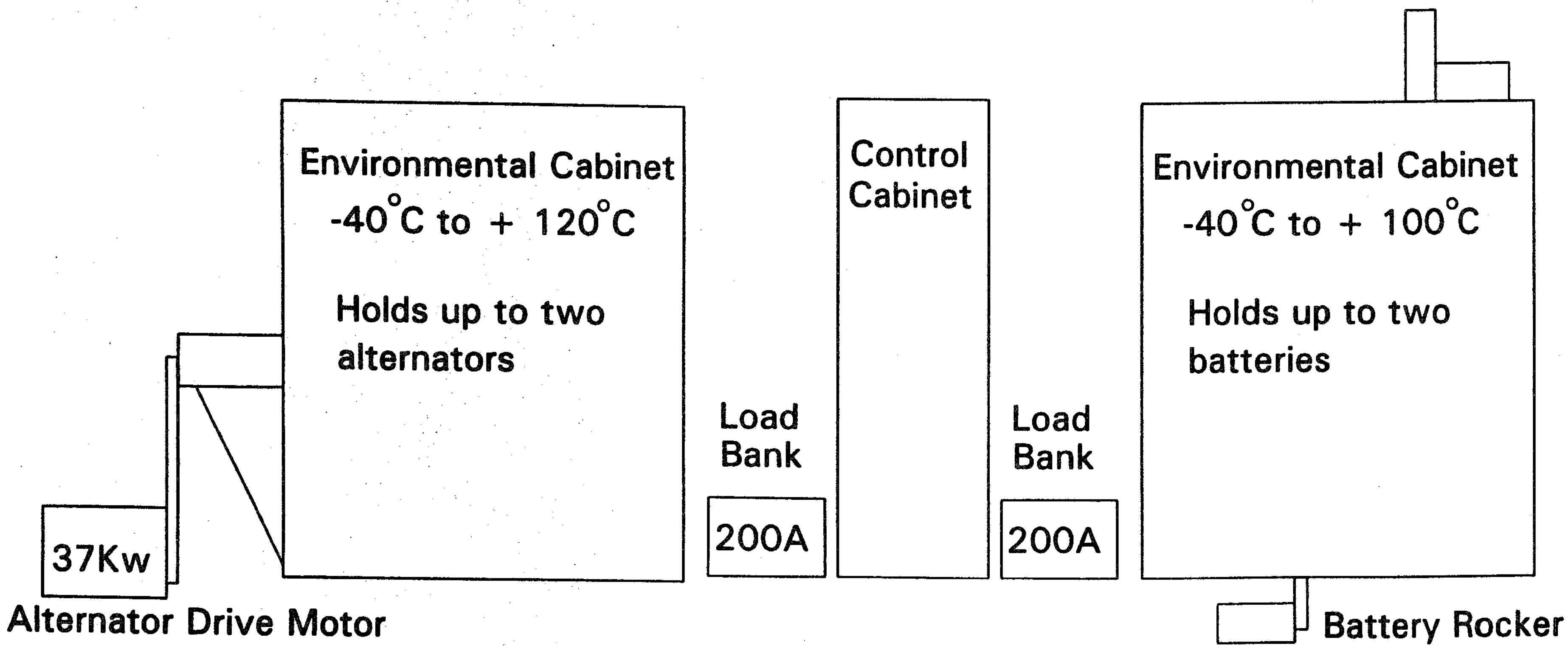
FIGURE 3

CHARGING SYSTEM TEST RIG

CIRCUIT DIAGRAM



GENERAL LAYOUT



As the XK8 project progressed, the electrical features fitted to the vehicle constantly changed. This is usually a source of great concern and uncertainty for charging system engineers owing to the limited accuracy of most computer based simulation programs which means that the actual effect of adding a particular feature is unable to be satisfactorily assessed until a vehicle is tested. This either results in reduced efficiency due to increased alternator size, (owing to engineers conservatism when under pressure to make a quick decision without all the relevant facts), or increased project costs in order to perform a test a in a climatic chamber which was not originally allowed for in the project plan.

However, for the XK8, provided that the load current and the functionality of the extra feature was known, then the effect on the charging system was determined by programming the feature into the rig test cycles and performing rig tests. As a result, Jaguar charging systems engineers are now able to provide a response on the effect of increased electrical feature within three days of the request being made, (dependant upon the level of re-programming required and whether the components fitted need to be changed), and this would be shorter if it was not physically limited by the time required to prepare the test batteries and normalise the components to the test temperature.

This provided a benefit to the XK8 as a number of extra features were added which, while benefiting the customer, required more power than the charging system could provide under certain conditions. As a result of test rig simulations, the operational mode of such features was modified such that they could be used whilst ensuring that the charging system was not unacceptably loaded.

The simulation test rig also aided in optimising the charging system components still further. Figure 4 shows the difference in charging performance obtained by changing from the originally recommended voltage regulator type to another, apparently less optimal one. The test results proved that the voltage/temperature characteristic of the original regulator provided inferior charging system performance, for the XK8 application, than the apparently less optimal type. The eventual change was only in the order of tenths of volts but the effect was significant and improved system efficiency. The rig was also used to prove that this new regulator did not significantly increase battery electrolyte loss and would not, therefore, reduce battery life.

Figure 5 demonstrates the change in alternator electrical refinement that occurred based on rig test results. Due to the need to rectify the generated power from AC to DC using a diode rectifier pack, every alternator has a small amount of 'ripple' inherent in its DC output. The initial alternator output waveform, (shown in Figure 5a), was not particularly 'clean' and contained an undesirable ripple and harmonic content which could possibly interfere with the vehicle audio system. Therefore, a number of modifications were made to the alternator to achieve the waveform shown in Figure 5b which was much smoother and had much reduced harmonic content. However, these modifications also reduced the alternator output power capability so, in addition to the test rig being used to obtain the noise measurements, it was also used to confirm that the performance of the charging system remained acceptable.

Therefore, prior to XK8 prototype vehicles being tested, Jaguar charging system engineers were confident that the optimal charging system components had been chosen and that, if anything unexpected was found during vehicle testing, the recursive rig and vehicle test procedures that were in place would help to quickly solve any problems and maintain the charging system performance at an acceptable level.

FIGURE 4

PERFORMANCE IMPROVEMENT DUE TO VOLTAGE REGULATOR MODIFICATION

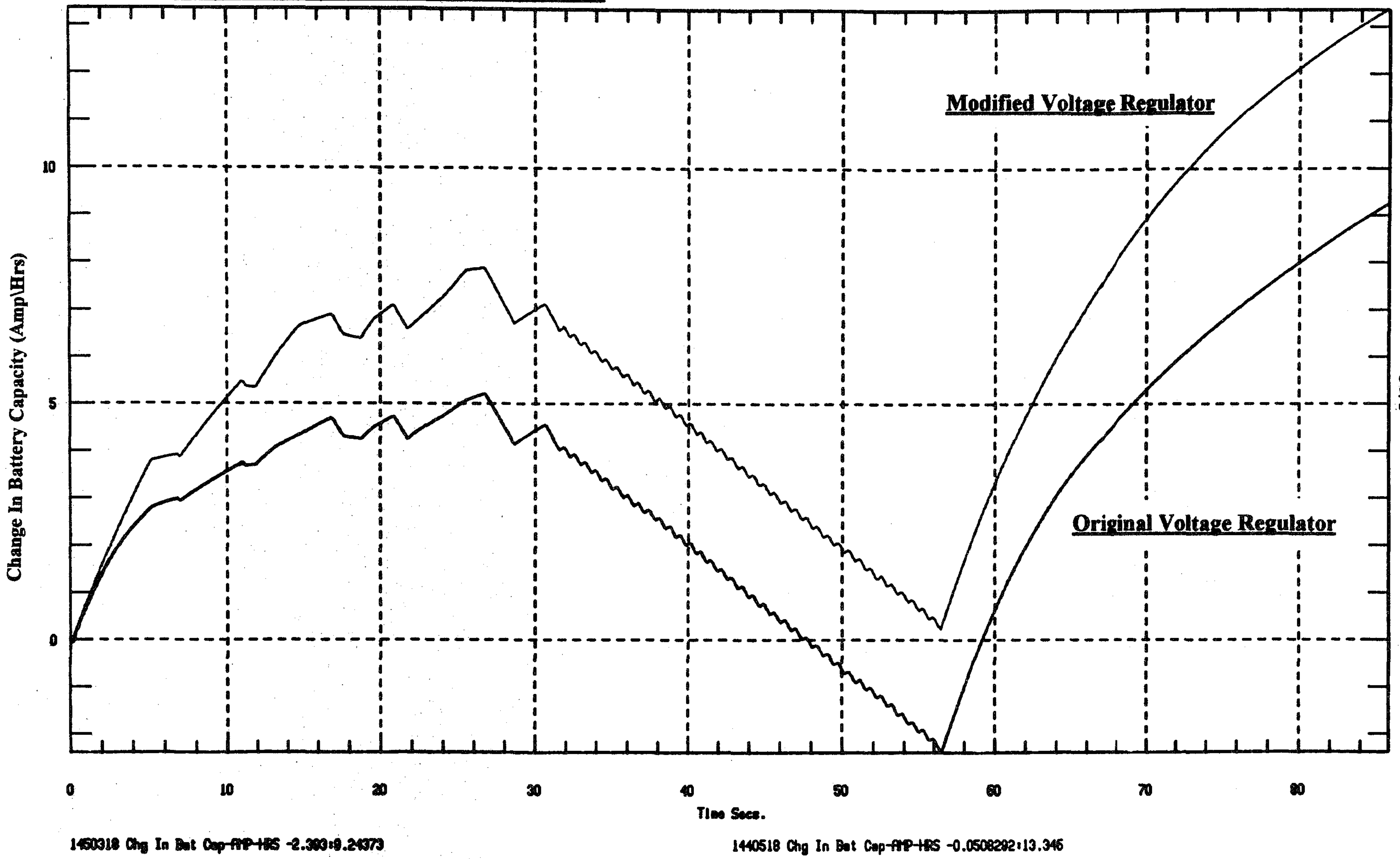
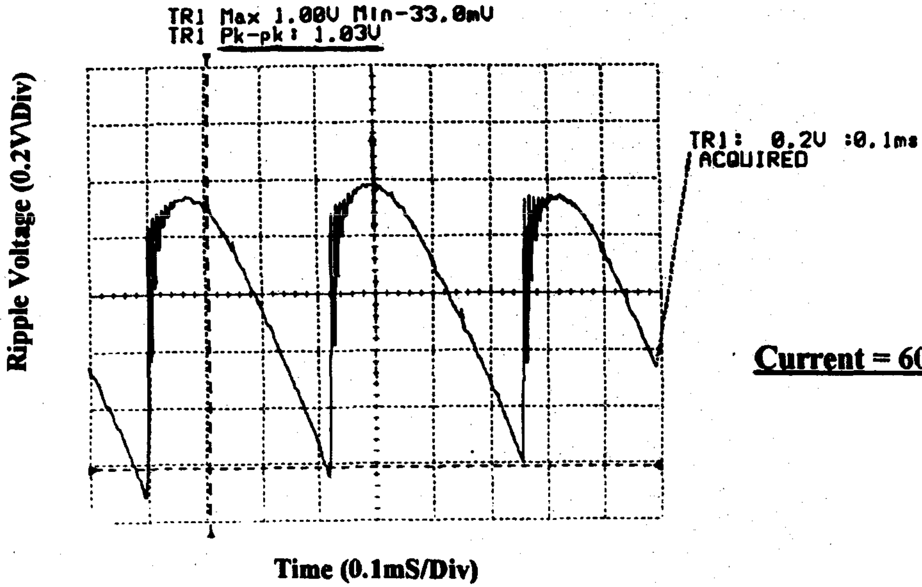


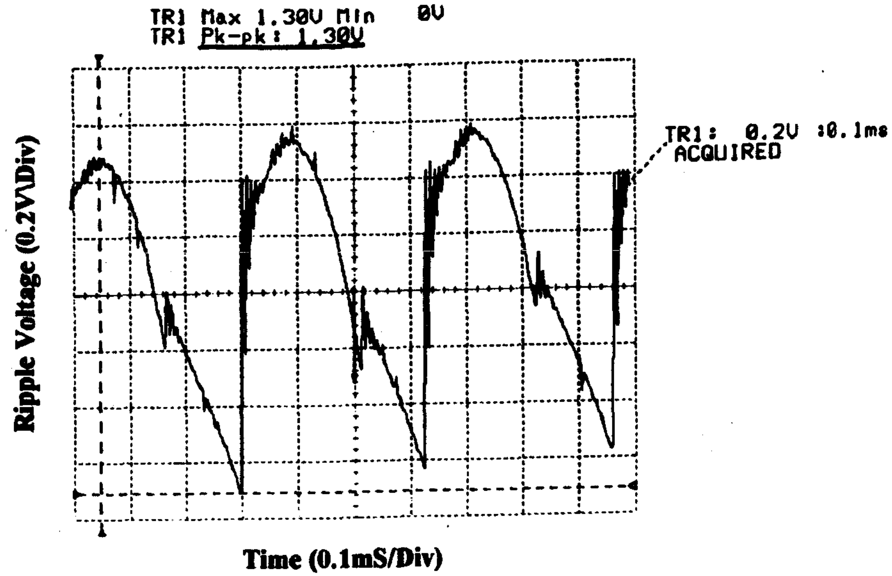
FIGURE 4

FIGURE 5 - IMPROVEMENT IN ELECTRICAL REFINEMENT

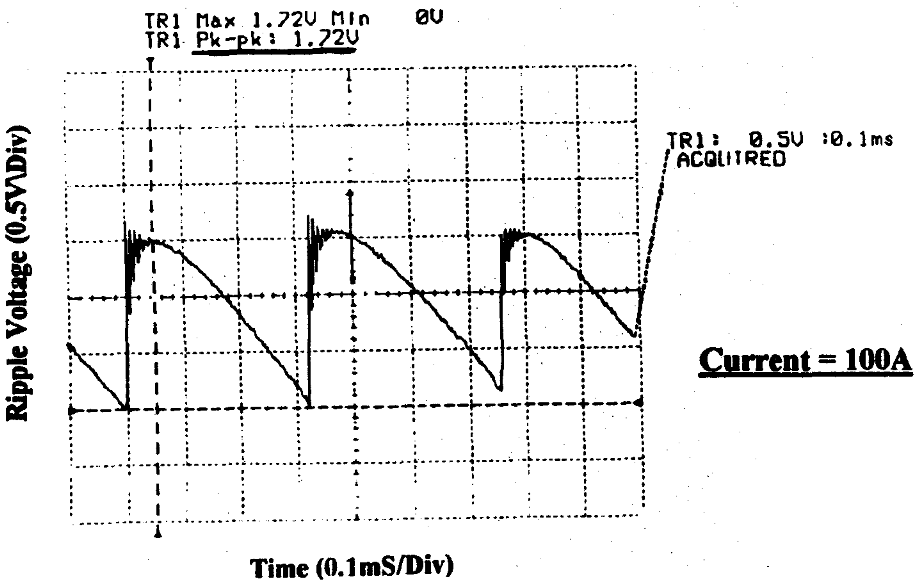
B - AFTER MODIFICATION

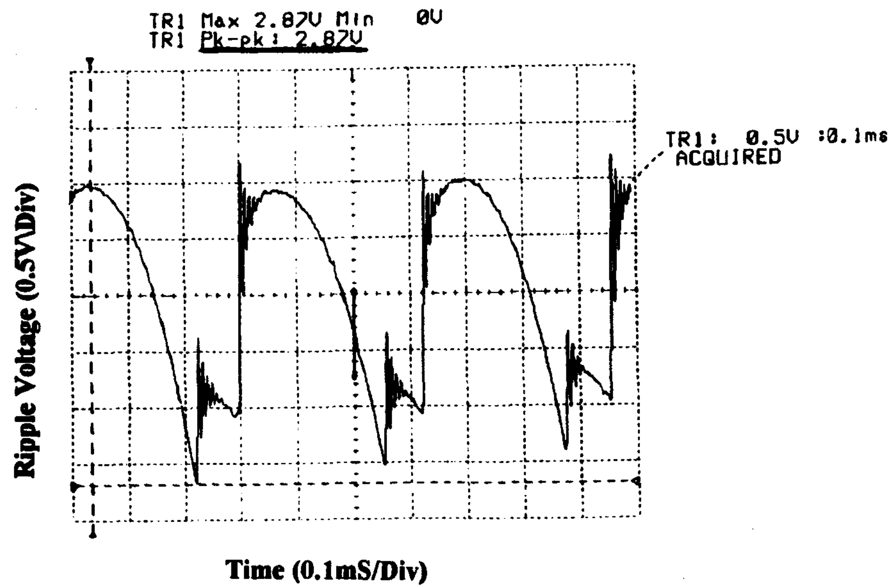


A - BEFORE MODIFICATION



Current = 60A





Current = 100A

4. VEHICLE TESTING

The early stages of simulation rig testing used the best available input data based upon tests of previous, different, vehicles and used calculated and estimated data from examining the intended component installations, the vehicle aerodynamics and its drive-train to estimate duty cycles. However, as such data was basically 'educated guesswork' charging system engineers started vehicle testing as early as possible in the XK8 project. At the earliest stage the vehicles used were 'simulators' which consisted of early versions of the XK8 powertrain fitted to XJS bodies so only data for component temperatures, engine speeds and very early indications of component duty cycles, was obtained. This data, though, was transferred back to the test rig to improve the accuracy of its results and improve confidence in the charging system.

Despite the use of the simulation rig, the charging system engineers still considered it necessary to test a significant number of prototype vehicles at each stage of the XK8 project. This was necessary in order to gather data, not only on charging system performance but also on the performance of other vehicle systems. As the charging system is almost the only system in the vehicle that is affected by every electrical or electro-mechanical system that is fitted, it is not sufficient to merely provide an alternator and battery that will support whatever the vehicle sub-system engineers demand. This would eventually lead to the electrical consumers going out of control to such an extent that there may not be an alternator powerful enough to support them. Therefore, it is necessary for charging systems engineers to examine the performance of as many sub-systems as possible in order to obtain data on their performance. This data and the personal experience of the engineers in driving the vehicles is then used as effectively as possible to allow more 'informed' discussions with the electrical sub-system engineers which then often leads to modifications being made which provide an acceptable compromise between the performance of the sub-system in question and its effect upon the charging system.

By following this process repeatedly, and in conjunction with increasingly accurate rig test simulations based upon the data fed back from the vehicle tests, it has been possible to fit more electrical consumers to the XK8 than was originally thought possible without having to use an unusually large alternator. In this way, the efficiency of the XK8 was aided by the charging systems sizing process.

Therefore, because of the use of the test rig early in the project, the XK8 prototype vehicle tests were used to enhance the charging system by attending to details such as aiding in calibrating the cooling and climate control systems as well as optimising the charging capability of the vehicle and setting up particular charging system related Engine Management System functions. At no time during the vehicle testing process was it necessary to test different alternators on the vehicle. Any changes to the components or additions to the feature content of the vehicle were simulated first using the test rig and vehicles were used simply to confirm that the rig test results were correct.

This recursive process of simulation rig and prototype vehicle testing continued up until the last prototypes built for sign off purposes. This was necessary in order to ensure that any changes to the vehicle that may have 'slipped by' the charging system engineers were detected when the vehicles were tested and, if the performance of the charging system was affected adversely, the cause was quickly identified and a plan put in place to recover the performance.

5. SUMMARY

The result of the process detailed here is that Jaguar charging systems engineers have more confidence than ever before in the performance of the charging system of a new model, despite the car having higher total electrical consumer demand than previous models and in addition to using a refined and low revving engine. Due to the efficiency of this process, Jaguar charging system engineers have been able to examine the performance of the XK8 charging system in depth over a much wider range of conditions than has previously been possible and believe that the best possible charging system has been provided within the constraints of the XK8 project.

This process has provided much improved traceability in the development of the charging system as every change has been documented with the reasons for such changes and their effects being detailed for future reference.

Work on the XK8 charging system effectively started during 1991 with the requirement to chose an alternator for the AJV8 engine and this process has been continually refined during that time with benefits passed onto other projects such as the 1995 model year XJ saloons. Consequently, whilst the process is continually being refined to improve efficiency, Jaguar are now in a position to develop a vehicle charging system in much greater detail than before whilst using less manpower to attain the results.

Therefore, whilst Jaguar charging system engineers are satisfied with the resultant charging system for the XK8, there are always areas that can be improved and our aim for the future is to ensure that Jaguar charging systems become more efficient and optimised than they are today by using the sizing process and design tools developed during the XK8 project.